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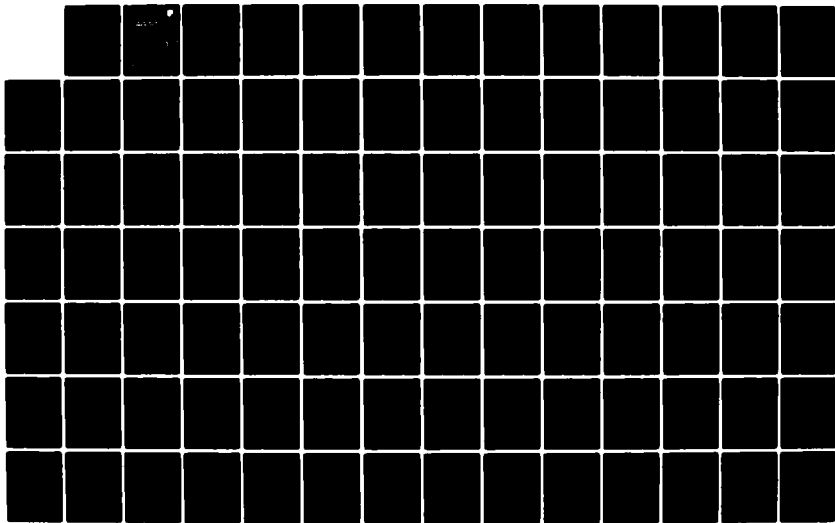
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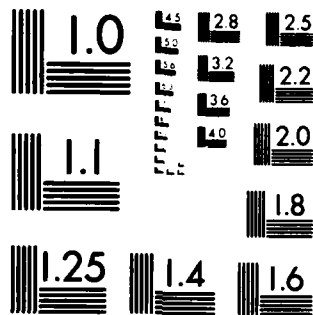
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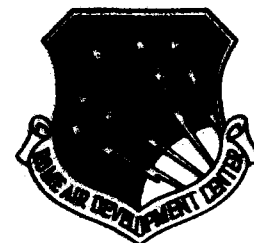




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January 1983



OPTION GENERATION TECHNIQUES FOR COMMAND AND CONTROL

Advanced Information & Decision Systems

**R. M. Tong, A. Arbel, S. O. Cloffi, C. M. Kelley, J. R. Payne and
E. Tse**

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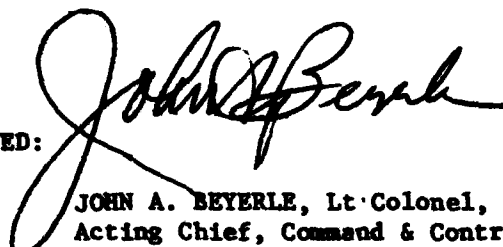
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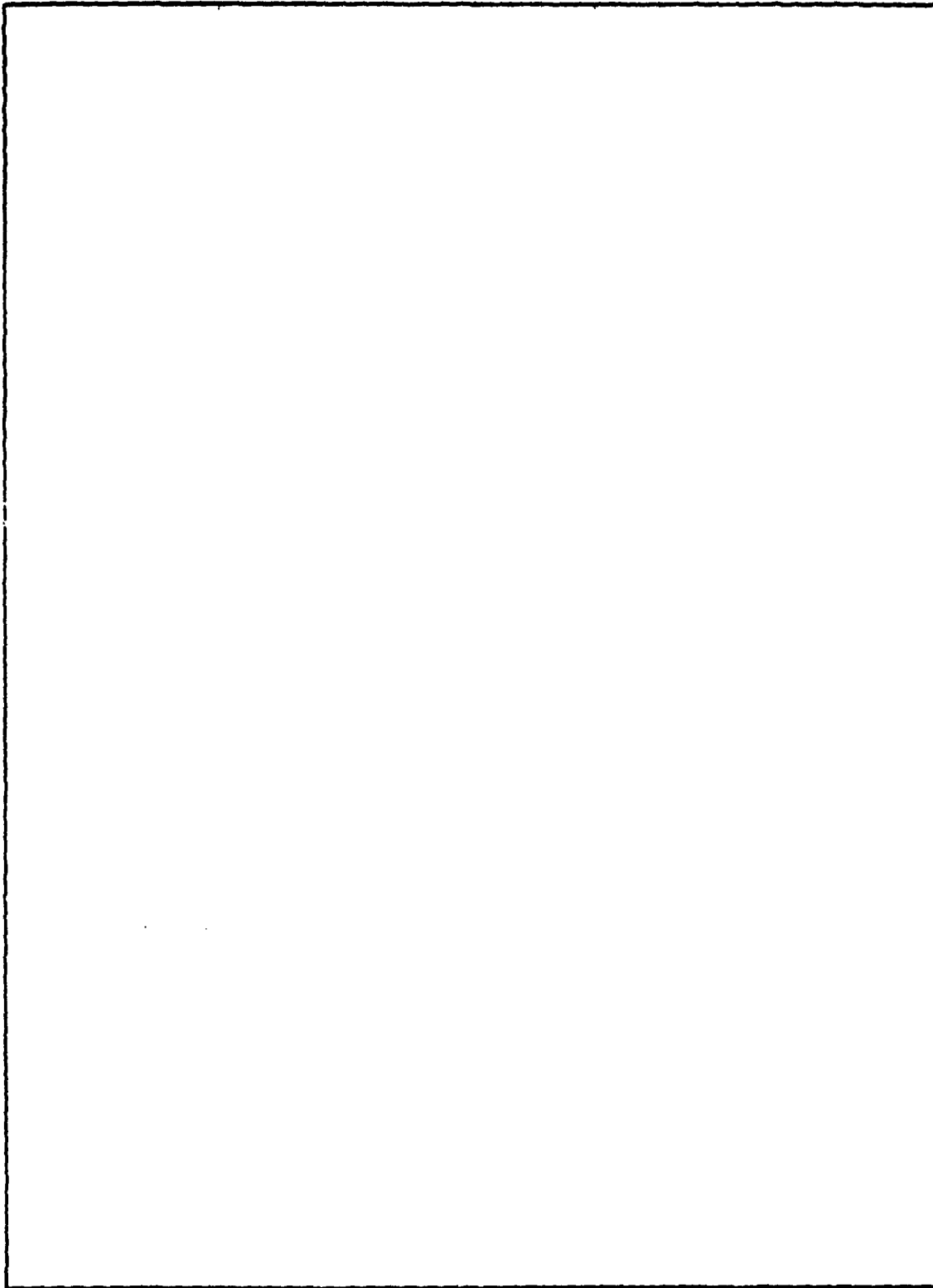
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TABLE OF CONTENTS

1. INTRODUCTION	1
2. LITERATURE SURVEY	6
A Categorization of the Literature.....	6
A Review of Key Publications	9
3. AN OPTION PROMPTING ENVIRONMENT	13
The Option Generation Problem	14
The Process of Decision Making	15
Creativity and Option Generation	21
Cognitive Biases and Styles	29
The Toolbox	33
A System Architecture for Option Prompting	37
4. THE ANALYTIC HIERARCHY PROCESS	42
Problem Representation	42
The Analytic Hierarchy Process	44
5. THE MONTEREY EXPERIMENT	51
Experimental Method	52
Results and Commentary	56
6. THE STANFORD EXPERIMENT	64
Experimental Method	66
Results	72
Discussion	81
7. SUMMARY AND CONCLUSIONS	88
Project Status	88
Future Research	92
Impact on Air Force Decision Making	94
ANNOTATED BIBLIOGRAPHY.....	98
APPENDIX A: SUMMARIZED BIBLIOGRAPHY	
APPENDIX B: A MATHEMATICAL DESCRIPTION OF OPTION GENERATION	
APPENDIX C: THE ANALYTIC HIERARCHY PROCESS	
APPENDIX D: STIMULUS FOR THE STANFORD EXPERIMENT	

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LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
3.1 The Decision Making Process.	16
3.2 Mapping from Decision Stages to Decision Task. .	19
3.3 A Componential Model of Problem Solving.	23
3.4 Interaction of Process and Componential Models .	28
3.5 An Option Prompting Environment.	39
4.1 Generic Hierarchy (Template)	46
5.1 Day 1 Problem Scenario	54
5.2 Day 2 Problem Scenario	55
6.1 Histograms for NUMBER Scores	75
6.2 Histograms for BREADTH Scores.	76
6.3 Histograms for NOVELTY Scores.	77
6.4 Histograms for FEASIBILITY Scores.	78
6.5 Histograms for BENEFIT Scores.	79
B.1 Attribute Space.	B4
B.2 Illustration for Options and Good Options. . . .	B12
C.1 Hierarchical Policy Evaluation	C2
C.2 Adjacent Levels in Hierarchy	C9

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1.1	Mapping Between Tasks in RTWS and Effort Described in Report	5
3.1	Some Common Biases.	31
3.2	Examples of Tools	34
6.1	Categories of Options	71
6.2	Statistics for Treatment.	73
6.3	Statistics for Field Dependence	82
A.1	Literature Categories	A2
A.2	Literature by Category.	A3
A.2	Literature by Category (Continued).	A4
A.2	Literature by Category (Continued).	A5
A.3	Literature by Topics.	A6
C.1	Comparison Scale.	C7

1. INTRODUCTION

Decision analysis is the systematic application of decision theory to problems of choice among alternatives. As such it has developed over the last two decades into a mature and powerful approach. It can be applied to a large number of problems, and there are many well developed techniques for assisting the decision maker in choosing among competing alternatives. For examples see Barclay et al[8], Holloway[34], Raiffa[64].

In practice, however, the decision maker may expend as or more much effort in specifying the alternatives (option generation) as he does in assessing their value (choice resolution). The vital role that option generation plays in the overall success of the decision making process is obvious. If the "best" alternative is not in the choice set, then it can never be selected.

Unfortunately, human decision makers are less-than-perfect gatherers and processors of information, are subject to a variety of cognitive biases, and display personal idiosyncracies in their decision making. It is not surprising then that when faced with difficult problems, and especially in times of stress, they exhibit demonstrably suboptimal option generation and choice resolution behavior.

Our primary task on this research contract has been to focus on option generation in novel and stressful situations, and investigate whether tools can be developed that would help the decision maker generate better sets of options. In our research we have first concerned ourselves with the reasons why decision makers perform so poorly, and

then used that knowledge to define what we have called an Option Prompting Environment. We have performed a thorough search of the appropriate literature and found few reports on the specific problem of option generation in decision making. There is, however, a significant body of psychology literature that deals with creativity and problem solving, and we have used some significant ideas from these sources in developing our approach.

Much of our early effort was devoted to developing the concepts of problem structuring tools, but our later work has attempted to define a broader generic view of the decision process so that option generation can be understood in its proper context. The resulting more comprehensive characterization of the decision process has led us to the conclusion that the option generation process depends on acquiring problem relevant data and domain knowledge, problem structuring, stating option , evaluating and refining options, and using procedures that are likely to evoke new ideas. Decision makers may perform these activities iteratively or in a more random fashion.

Recognizing the importance of formal testing of decision aids, we have performed two separate experiments that were designed to explore and evaluate our ideas. We have used the results so obtained to guide our thinking about what constitutes an appropriate decision making environment, and the types of tools that should be included in that environment to enhance the option generation process.

The Air Force is willing to invest relatively large amounts of money, time and effort in the explicit training of pilots, other operator personnel, and technicians; but little for explicit training of

Generals and staff officers in one of their most important activities: command decision making. Providing decision support systems such as Option Prompting Environments would provide mechanisms for both staff colleges and operational staffs to focus efforts in this area. In particular, it may encourage them to focus on making "better" decisions (i.e., generating and selecting a "good" alternative) instead of immediately developing a plan for an "OK" alternative.

The remainder of this technical report is organized into six chapters and a number of appendices. Chapter 2 contains a discussion of the literature we have surveyed. There is a large amount of material that deals with the general question of decision making and problem solving, so we have attempted to categorize the literature into several useful domains. We have restricted our review in this chapter to those papers that we have designated as being significant to an understanding of the option generation problem and our view of it. A fully annotated bibliography begins on page 98 of this report.

In Chapter 3 we develop our concept of an option prompting environment. We start by examining the overall decision making process and describe several models that help us understand why decision making can be less than optimal. We then use some recent ideas from the psychology of creativity to define the properties that an option prompting environment should have. The role that cognitive biases and styles play in this environment is then examined. Central to this environment is the provision of a set of tools that the decision maker can draw upon. We define some appropriate classes of tools and rules for their use. To conclude the chapter we describe an outline for a

computer system architecture that would support an operational definition of our environment. Some mathematical interpretations of the issues in option generation are given in Appendix B.

In Chapter 4 we consider tools for helping the decision maker structure the decision problem and arrive at priorities among decision factors. A significant part of our effort has been in developing and evaluating a computer implementation of the Analytic Hierarchy Process which we believe to be a particularly useful technique. We describe this methodology, review its effectiveness and suggest areas for further development. A more detailed, and mathematical, description of AHP is given in Appendix C.

Our first experiment is described in Chapter 5. This was designed to test the concept of AHP as a structuring tool, and we report on the procedures used and the lessons learned. For our second experiment, described in Chapter 6, we chose to re-test our AHP software together with a simple version of the option prompting environment. We also performed a series of secondary experiments to try and correlate performance in the main experiment with performance on various cognitive style tests. The stimulus material used in the second experiment is included in Appendix D for reference.

In the final chapter we survey the status of the project and suggest areas for further research and development. We also attempt to assess the likely impact of an operational option prompting environment on Air Force decision making.

A mapping between the four tasks defined in the original Research and Technology Work Statement and the report is shown in Table 1.1.

Table 1.1. Mapping Between Tasks in SOW
and Effort Described in Report

TASK	REPORT SECTIONS
<ul style="list-style-type: none"> Analyze and document literature 	<ul style="list-style-type: none"> Chapter 2; Appendix A
<ul style="list-style-type: none"> Define techniques for option generation 	<ul style="list-style-type: none"> Chapters 3, 4; Appendix B, C
<ul style="list-style-type: none"> Provide and define experiments 	<ul style="list-style-type: none"> Chapters 5, 6; Appendix D
<ul style="list-style-type: none"> Analyze impact on AF decision making 	<ul style="list-style-type: none"> Chapter 7

2. LITERATURE SURVEY

There is a substantial amount of work reported in the literature that has potential relevance to the problem of option generation. We have attempted to do three things in our survey: compile an extensive bibliography, partition the entries into a variety of categories, and highlight the key papers. This chapter describes the major categories we have chosen and reviews the papers we believe to be most important in understanding the option generation problem. A more detailed survey is given in the annotated bibliography and in Appendix A.

2.1. A Categorization of the Literature

In our search for relevant literature we have found that many disciplines are concerned with understanding how solutions to problems are generated. Perhaps this is not surprising, since a great deal of human effort is devoted to exactly this task. Indeed,

For the purposes of our survey we have made a distinction between those disciplines that concern themselves primarily with the psychological processes of decision making and those disciplines that address the situational aspects of decision making. In the former, "internal", category we have placed psychology, cognitive science and artificial intelligence. In the latter, "external", category we have placed decision analysis, management science and systems engineering. In

practice this partition is fuzzy since many studies are concerned with both the internal and external issues in decision making. Nonetheless, all the literature that we have considered has as its goal either the development of models of decision making and problem solving, or the definition of appropriate procedures for improving the quality of decisions.

Another useful way of dividing the literature is into various subject categories. We have defined five categories that reflect the range of issues that arise in option generation. First, we have looked at studies in behavioral decision theory. These concern themselves with psychological aspects of judgement and choice, and are particularly concerned with patterns of behavior for coping with uncertainty. The literature on cognitive biases and styles is included in this category.

Our second subject category is creativity, and we included studies designed to define, measure and improve it. This category is very broad, ranging from formal psychological investigations to "popular" suggestions for improving personal problem solving behavior.

The third subject category is decision support systems (DSS). Again, this is a rather broad classification devised to encompass any studies that discuss the design and implementation of tools, or systems of tools, for helping decision makers. The tools may be elaborate, an extensive management information system (MIS) for example, or simple, such as straightforward checklists for routine tasks.

The fourth subject category is concerned with methodological questions. In particular, we include studies that look at the design of experiments and appropriate measures of performance. The final category

is problem solving. This is least clearly defined and is something of a catch-all. In it we have placed studies in organization theory, planning, formal reasoning and decision analysis.

A further possible categorization is by study type, and we have distinguished four kinds. First, there are studies that are primarily concerned with experimental verification of hypotheses about decision making behavior. Second, there are studies whose main concern is with the detailed implementation of decision aids, be they computerized decision systems or formal procedures. Third, there is a broad class of studies which we consider to be of a theoretical nature. These include work on mathematical theories of preference and choice, presentations of psychological theories of problem solving, and philosophical enquiries into the foundations of human reasoning. Finally, several authors have attempted reviews and surveys of the various literatures and we include these in our miscellany category.

Obviously, there are other ways in which this partitioning could have been performed. However, we believe that our approach is adequate for introducing the literature and avoids the fragmentation that a more precise categorization would give. The scope of our search has been restricted to English language publications, but otherwise we have attempted as broad a view as possible. No doubt we have overlooked some work that is relevant, but by including in our bibliography several review and survey articles, we hope that everything significant has been referenced at least indirectly.

2.2. A Review of Key Publications

As we develop our view of the Option Generation problem in subsequent chapters we will refer explicitly to some important work that has influenced our thinking. The purpose of this section is, therefore, to highlight studies that provide insight into the multiplicity of issues that impinge on Option Generation.

There has been much interest in behavioral decision making and two excellent extensive reviews have appeared. Slovic, Fischhoff and Lichtenstein [71] concentrate on heuristics and biases referencing over 300 publications; Einhorn and Hogarth [19] discuss the question of normative versus descriptive approaches to human decision making and reference over 150 publications. More recently, a collection of papers has appeared edited by Kahnemann, Slovic and Tversky [45] which includes many of the key publications on this topic.

Perhaps the main result of all this effort has been the recognition that man is a less-than-optimal gatherer and processor of information. He exhibits a wide range of systematic biases in all stages of decision making and often displays personal idiosyncracies thus impairing his ability to make fully considered decisions.

While much experimental evidence has been gathered, a comprehensive theory of biases that would allow us to predict when they will operate has yet to appear. Indeed, there is a debate over the validity of the effects observed, with many questions about the confidence we should have in translating the results of the laboratory studies to "real-world" decision problems.

There seem to have been few efforts to study the option generation process directly with the work of Gettys et al and Pitz et al being the most prominent. In [23] Gettys et al report on a series of experiments designed to test the adequacy of option generation performance. This work is notable for its development of a methodology for measuring performance. The main finding was that subjects failed to generate important options and that this was often costly. In [25] they attempt to construct a model of the way in which decision makers generate hypotheses about data. The model is based on Bayes Theorem with the idea that new hypotheses are only generated, or retrieved from memory, when the currently active set has low "plausibility". Their experimental data seems to provide some support for the model. A general overview of this body of work is given in [24].

In [60] Pitz et al examined reasons why decision makers omit certain decision alternatives. In performing their experimental work they discovered that focusing on objectives was an effective way of generating choices. Furthermore, considering the objectives one at a time was observed to be better than considering them all at once. In [61] they extend this work and conclude that a scenario script (or template) approach to problem structuring is the most effective procedure since this matches human tendencies to think in terms of action-outcome scenarios.

Human creativity is a subject that has been widely studied both by the academic community and by a variety of "lay" practitioners. We have found the theoretical work of Amabile [4],[5] to be particularly insightful. Her view of creativity as being dependent on domain

knowledge, motivation and creativity skills helps understand some of the very widely differing results of creativity research. An older, but very comprehensive, discussion of the role of creativity in human endeavour is given in Koestler[47], and at a less theoretical level, the work of Adams [2] is an excellent example of the design of procedures which can help overcome certain kinds of mental blocks (biases).

There have been several attempts to build computerized aids for decision making where the emphasis has been on problem structuring. See for example the work reported by Gulick[27] and by Merkhoffer et al [53]. While most of these use conventional decision trees, the work of Pearl et al [59] is substantially different. Their basic premise is that in many, if not all, real-world applications the decision maker does not perceive the problem as a time sequence of decision alternatives and event outcomes. Rather, he sees a static network of influences surrounding issues and factors. Thus when the decision maker confronts a complex problem he does not think in terms of the alternatives available to him, but in terms of his desires and concerns. This leads the authors to consider an alternative structure for representing the decision maker's knowledge as a hierarchy of goals and sub-goals with a complex form of sensitivity analysis used to guide the search through the goal network. The authors claim that the goal directed approach is superior in both clarity and purposefulness and that the explicit mention of objectives helps the decision maker evoke unconventional alternatives capable of realizing those objectives.

Finally, Wohl [85] provides an excellent overview of the issues and decision requirements for Tactical Air Force Command and Control. The

focus is on the requirements of the human decision maker in a variety of contexts (both preflight and inflight). He shows how decision aids can be assessed in terms of a behavioral model that distinguishes between stimulus (data), hypothesis (perception alternatives), options (response alternatives) and response (actions).

We consider each of the works mentioned above to be a good introduction to their respective views of human decision making, and they provide a convenient base for exploring the issues in more detail. Appendix A contains our own annotated bibliography.

3. AN OPTION PROMPTING ENVIRONMENT

In this chapter we will present our view of the Option Generation problem and discuss a basic construct that we believe provides the foundations for a comprehensive solution. We have attempted to construct only the theoretical skeleton of this solution, concerning ourselves with structuring and exploring the validity of our primary concepts rather than with questions of how the solution might be implemented.

Our basic insight is that the decision maker needs an Option Prompting Environment rather than one specific option generation aid. We will show how we have been led to this view by first discussing the relationships between option generation and the rest of the decision making process, and then by considering the reasons for poor performance on the option generation task. We define the characteristics of the environment by drawing on work in the psychology of problem solving, and, in particular, consider the role of decision maker creativity. Cognitive biases and styles have concerned many workers in decision making, and we review this work in relation to options generation and our solution. A feature of our environment is that the decision maker is given access to a variety of potential aids; so we discuss the concept of a "toolbox" and the rules for its use. Finally, we outline an architecture for a computerized version of our environment and discuss its main components, showing how these reflect the concerns raised in the earlier parts of the chapter.

3.1. The Option Generation Problem

Stated simply, when the decision maker is engaged in the task of option generation he is attempting to define a set of choices, or action, alternatives to which he can apply some appropriate normative technique for selecting the best. We feel that option generation is a vital, and yet neglected, part of the decision making process. This is somewhat surprising since one could argue that the value of decision analysis is primarily in the structuring it gives to such open problems.

"Practiced decision analysts ... report that a major part of many studies is the specification of the set of alternative courses of action."

Watson and Brown[79]

We will make a distinction between what we term "closed" decision problems, such as buying a new car, and "open" ones, such as rescuing the hostages from the embassy in Tehran. A closed problem is one in which the option generation task is straightforward, either because the problem is routine or because the number and type of options is defined by the problem. An open problem on the other hand is characterized by being novel and by having no clear a priori bounds on the possible solution set. Furthermore, the "openness" itself often induces stress in the decision maker causing even further deterioration in his ability to think rationally about the problem.

Our efforts on this contract have been directed towards option generation for open problems. Central to our view is the assumption that the actual act of option generation cannot be automated. It is essentially a creative activity that can only be performed by the

decision maker. All we can hope to do is enhance this creativity. We will return to this point later and for now concentrate on the overall decision making process and discuss some reasons why decision making is often less than perfect.

3.2. The Process of Decision Making

Figure 3.1 shows a model of the various stages of decision making. This breakdown into six distinct phases is by no means unique, and other authors have presented similar structures. See for example Hogarth[33]. The purpose of this model is to show that the decision maker has to perform several different functions as he moves from recognizing that he has a problem, to implementing his preferred choice.

The most important features of this model are the feedforward and feedback loops. Their purpose is to emphasize that decision making is not a linear progression from one stage to another. Rather, it is essentially iterative, with the decision maker moving as required between the elements we have shown. with the movement being regular or seemingly random To illustrate the concept, suppose the decision maker realizes that the problem is one that he has seen and successfully dealt with before. In this case, he can dispense with a detailed problem structuring effort, does not need to create possible solutions or assess their relative merits, and can proceed immediately to an implementation of the solution. This is indicated in our model by the feedforward loop from problem recognition to implementation and review. Such "stimulus-response" decision making has been of little interest to us in this context; it corresponds to typical behavior in what we have called closed problems.

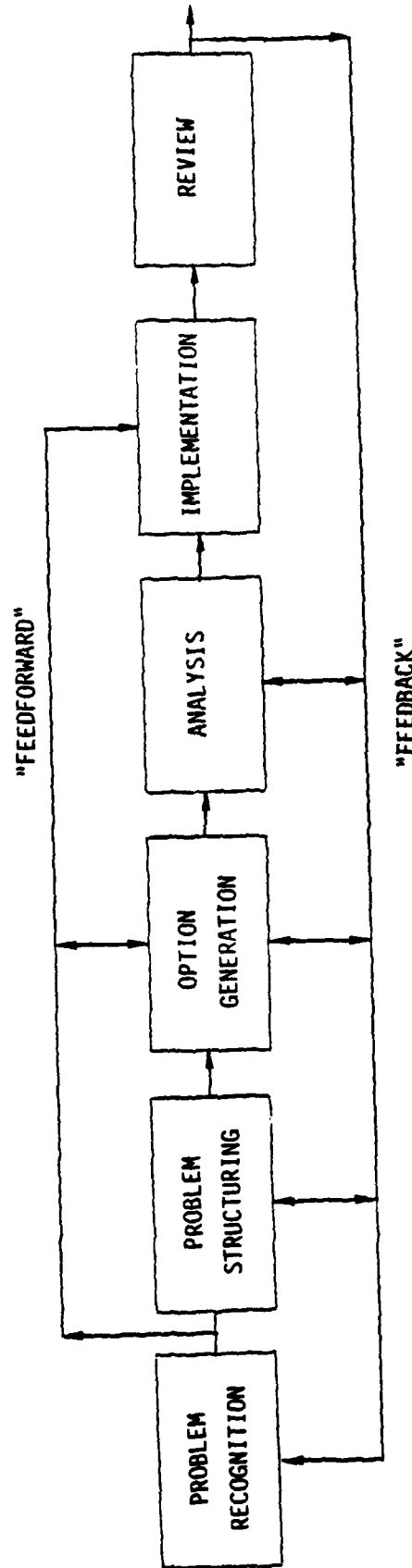


Figure 3.1. The Decision Making Process

Much more challenging is to describe typical behavior in an open problem. In such cases, the decision maker will engage in activities in each of the six blocks in our model. Faced with a novel problem, the decision maker will probably want, and gather, as much information as possible about the specific decision situation. He will use this information, together with his own domain knowledge, to begin structuring the problem. This somewhat vague concept involves a determination of the major factors that the decision maker believes influence the problem. These might include the decision maker's goals, the goals of the other actors, the constraints imposed by the environment and the resources that the decision maker can bring to bear on the problem either directly or indirectly. As his understanding of the problem increases, the decision maker will begin to think about possible solutions in addition to any he may have thought of when he first became aware of the decision situation. Depending upon his personal style, he may attempt to evaluate the feasibility of the options as soon as he thinks of them, or he may generate as many as possible before proceeding to the analysis of specific options. It is quite conceivable that as options are generated and evaluated the decision maker's view of the problem changes. He might engage in a cycle of structuring, option generation and evaluation until he is confident that his understanding of the problem is complete. Only at this point will he proceed, first to a formal analysis of the options and then to implementation of his choice. Even then, though, the overall cycle may not be completed. In many instances, the outcome of decision making is a plan of action, and it is an important part of the decision maker's function to monitor the execution of the plan. While

doing this he may become aware of new information about the situation which would lead him to revise his initial decision. Depending upon the magnitude of the deviation from the outcomes originally conceived, this revision may take the form of a drastic restructuring or just a simple modification.

Our model can thus provide a descriptive account of a set of typical decision behaviors. Its main purpose, however, is to show that options generation is intimately connected with the other parts of the decision making process. It makes little or no sense, therefore, to treat the option generation problem in isolation. If we do, then we are ignoring the essential iterative and interconnected nature of the decision making process. It is important to understand, and take account of, the various functions the decision maker has to perform, and we have to examine how these affect the central question of options generation.

Having described the nature of the overall decision making process, we need to ask why it is that decision makers often find it difficult to generate options for open problems. Unfortunately, as our literature survey has shown, there are no truly satisfactory explanations and we can conclude that there are a variety of reasons which are more or less relevant for different decision makers in different contexts.

Our approach to this question is to construct a model of "tasks" that parallels the process model described above. That is we ask ourselves what tasks does the decision maker engage in when performing the functions show in our first model. Figure 3.2 shows how the tasks map onto the process stages. Thus during the problem recognition and

TASK STAGE	INFO. GATHERING	MODEL BUILDING	PROBLEM SOLVING	OUTCOME EVALUATION	PLAN GENERATION	STATUS MONITORING
RECOGNITION	X					
STRUCTURING	X	X				
OPTION GENERATION			X	X		
ANALYSIS				X	X	
IMPLE- MENTATION					X	
REVIEW						X

Figure 3.2. Mapping from Decision Stages to Decision Tasks

problem structuring phases, the decision maker is primarily engaged on tasks of information gathering and model building. At the point at which he generates the options, we can imagine he is engaged on a task of creative problem solving. Choice of option is supported by careful assessment of outcome values and probabilities. Finally, implementation and review requires the decision maker both to prepare and issue orders and to get specific information about the evolution of his plan.

This task model gives us a structure for understanding why the overall decision process, and option generation in particular, may not be performed effectively. First, the decision maker may simply not be getting enough relevant information about the problem. He may not even be aware that a problem has arisen until it is too late for him to generate an appropriate response. Second, he may not be making adequate use of the information he does have. Thus, for example, the model he constructs of the problem may not include important elements. This could be through ignorance, but more likely through oversight. Even if his view of the problem is adequate, the decision maker may not be able to define a solution. The deficiency here is one of under-utilization of creativity skills. It is during decision analysis that the majority of cognitive biases operate. These act primarily to reduce the efficiency with which information is gathered and processed. Difficulty in choosing an option for implementation even after a formal decision analysis may be due lack of confidence in the models used for the analysis. Penultimately, the decision may be ineffectively implemented because of inappropriately formulated, or poorly communicated, plans. Then finally, monitoring may also be defective, leading to missed cues

and inadequate responses to changes in the problem context.

Most of these potential reasons for poor decision making stem from the human decision maker's cognitive limitations. It must be, therefore, that if we are to help then we should provide tools which can be used to offset this weakness. Since, as we have mentioned, there are no predictive theories of cognitive weakness we must rely on providing a set of tools from which the decision maker can select and use as necessary. We will describe the contents of the toolbox in a later section, and for now ask what we must do to encourage the decision maker to recognize his limitations and work with the tools we can provide. That is, we need to consider the environment in which the decision maker is to operate.

3.3. Creativity and Option Generation

In our discussion so far, we have shown that options generation is central to the decision making process. We have also shown that it is not possible to consider the generation of option in isolation, and have considered some reasons why performance on this task may be inadequate. Underlying this discussion is the basic belief that, since the decision maker is the ultimate source of all option, the function of our proposed environment is to enhance his ability to generate a rich set of options. If we take this point of view, then we need to examine carefully the nature of the environment we create. We need to understand both its general characteristics and its specific components, and we need some psychological theory to help us build a secure foundation for our design.

In the kind of open decision problem in which we are interested, the decision maker is usually faced with a set of complex and unusual circumstances. His task is to find potential solutions despite this complexity, and it will be characteristic of these solutions that they both draw together diverse aspects of the problem and are insightful. Another way of describing such behavior would be to label it "creative", and we believe that by doing so we capture the essence of the option generation task.

"The generation of alternatives ... require(s) much imagination and creative thinking."

Hogarth and Makridakis[32]

The concept of creativity as a cognitive process has been studied extensively, and there have been many attempts to define what it is to be creative and how, if at all, creative behavior can be encouraged. Unfortunately, there does not appear to be a consensus among those working in the area. This situation is exacerbated by the corresponding lack of any convincing experiments; most claims being based upon anecdotal evidence and subjective testing. However, an attempt to integrate and explain all the apparently conflicting views of creativity has recently appeared, Amabile[5], and in this model we find what we need to help us define our option prompting environment.

The key to Amabile's model lies in its recognition that both motivation and problem domain knowledge are necessary if the decision maker is to make effective use of his inherent creativity skills. Thus we have a "componential model of creativity" as shown in Figure 3.3 where we indicate how the three major components interact with one

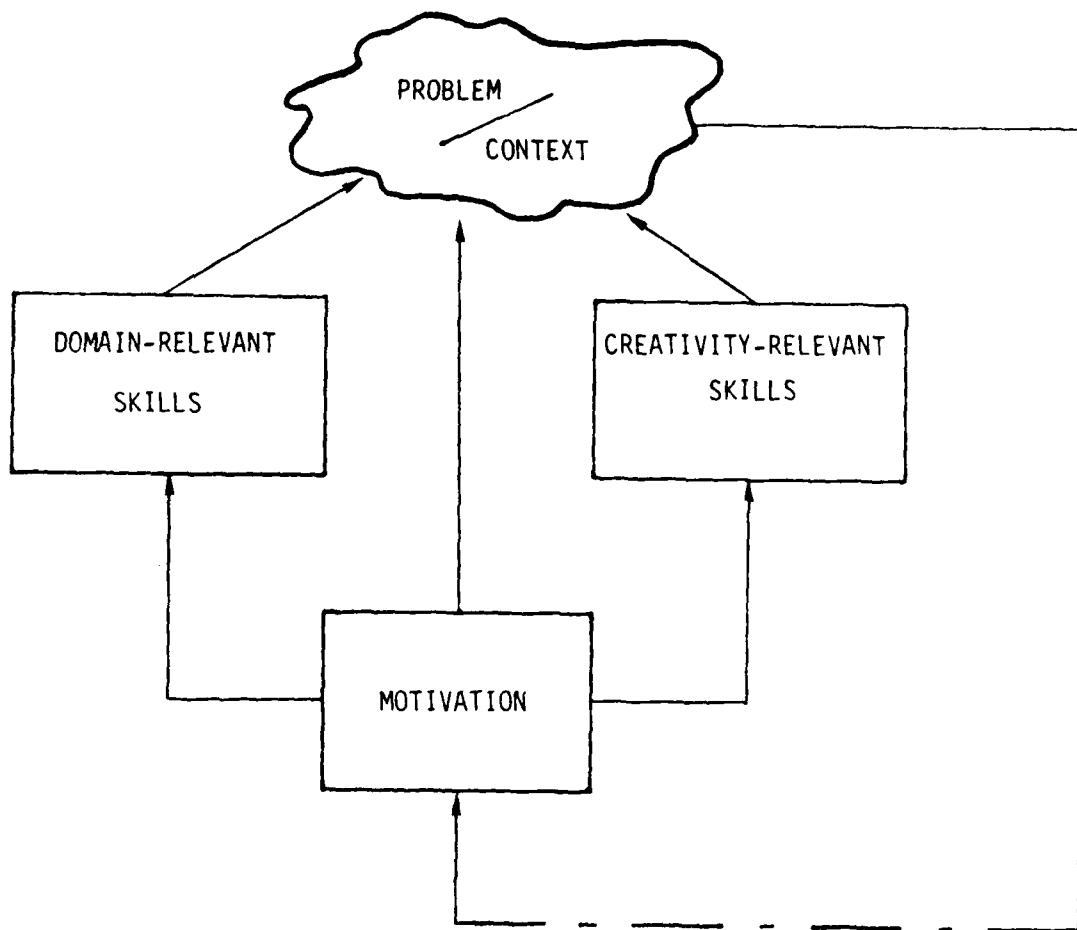


Figure 3.3. A Componential Model of Problem Solving

another and with the problem. The fine structure of this model is not yet worked out, but in our search for some insight into the nature of the options prompting environment it is not necessary that we have a detailed psychological description of how skills are learned or how they interact with motivation. All we need, in fact, is a coarse understanding of the main components and how they are interconnected.

Task motivation has powerful effects on performance, although the exact mechanism is unknown. It accounts for the motivational variables that determine the decision maker's approach to a given task, such as: initial level of intrinsic motivation, presence or absence of extrinsic social constraints, and individual ability to minimize the cognitive effects of extrinsic constraints. One interpretation of the effects of motivation is that it changes people's level of physiological arousal. For example, a sleepy person will actually become more aroused if he begins to perform a task. The Yerkes-Dodson Law [86] states that performance is a curvilinear function of arousal; that is, performance initially improves with increasing arousal, but will deteriorate if arousal continues to increase. Therefore, if people are overaroused, perhaps by excessive motivation, the likelihood that they will think of a variety of solutions to a problem decreases. Potential problem solving aids could focus on increasing or decreasing motivation, to maintain it at an optimum level.

Domain-relevant knowledge is a limiting factor in the types of option people can generate. It includes factual knowledge about the problem, technical skills and special talents. Clearly, people cannot arrive at a solution which depends upon knowledge they do not possess.

although they may generate a partial solution, recognize the gap in their knowledge base, and seek out the necessary missing information. However, domain relevant knowledge is not limited to sets of facts. Experts do not simply know more than novices. Experts and novices begin their problem representations with different problem categories, and then complete the problem by retrieving knowledge associated with the categories. For example, experts in physics categorize physics problems as examples of abstract physics principles, whereas novices base their representation of the problem and subsequent problem solving approach on the problem's literal features (Chi, Feltovich, and Glaser [12]). The expert's qualitative knowledge is typically tacit, and cannot be quickly transmitted to novices.

The third component, creativity skills, includes cognitive style, implicit or explicit knowledge of heuristics for generating novel ideas and working style. The decision maker may have a collection of general tactics which he applies to problems, such as thinking backward from the goals to the given state, breaking up the problem into subproblems, generating alternative representations of the problem, or searching for an analogous problem which has already been solved (Wickelgren [80]). Creativity skills appear to be the component most amenable to external aids. Although numerous books are available on how to stimulate creativity and problem solving (Adams [2], Osborne [57], Gordon [26]), their impact has not been great. First, most of the methods of increasing creativity or creative problem solving have not been evaluated experimentally (Campbell [11]). Studies that have been done have mainly studied artificial problems, such as uses for a wire coat

hanger. An exception is a study by Basadur, Graen and Green [9] which found improved problem finding by engineers given a two day creativity training seminar, but they did not assess actual problem solving performance. One problem of extensive creativity training programs is that the results may not generalize to performance outside the training program. When the facilitation and guidance of the program leader is no longer available, people may be unable or unwilling to use the suggestions when they are actually confronted with a problem.

This description is not meant to be a complete exposition, but is merely meant to illustrate Amabile's claim that the three components do form a necessary and sufficient set of factors for understanding creative behavior. Thus in terms of Figure 3.3, we see that without a sufficient level of motivation the decision maker will not even begin to consider the problem. Once he does though, he needs to have both domain skills and creativity skills. To some extent these can both be learned, but both will be applied more effectively if task motivation is high. All the components interact with the problem, and as the decision maker perceives himself moving towards, or away from, his goal, or sub-goal, then his level of motivation will be modified thus providing the necessary feedback to drive the problem solving process.

Even at this macroscopic level we can draw some inferences from the model about the properties our environment should possess. First, it must help the decision maker maintain his interest in the problem. It might do this by ensuring that there are several tools available for him to use for any given sub-task that he is engaged upon. Second, the environment should allow him to make the best use of, and maybe even

improve, both his domain and creativity skills.

We can get even more insight by considering how the components of Amabile's model interact with the stages in our process model of decision making. This interaction is shown in Figure 3.4. We have collapsed the implementation and review stages into one called "Outcome" to emphasize that the feedback to motivation occurs at several points. Notice that both creativity skills and task motivation directly affect option generation. This implies that if the environment is to help at all at this crucial stage, it can do this best by making the decision maker engage in activities that help him "break set". That is tasks designed to aid him view the problem from many, maybe superficially contradictory or ridiculous, perspectives. This mapping from the psychological framework to the decision process framework also indicates that the specific tools we provide may be categorized not only by the task that they help support, but also by those components of Amabile's model that they most address. The possibility of providing tools that only help develop skills, or increase motivation, thus arises. We discuss these ideas in more detail in the next section.

To conclude this section we consider the problem of measuring creativity. Most writers on the subject of creativity define it in terms of the end product. That is, given a problem, a solution is creative if it is sufficiently different from what has been suggested in the past and is at the same time workable. This definition is satisfactory in so far as it applies to problems that have clear solutions. It is typical, for example, of the tests a patents officer might apply to a new device that is given to him for possible licensing.

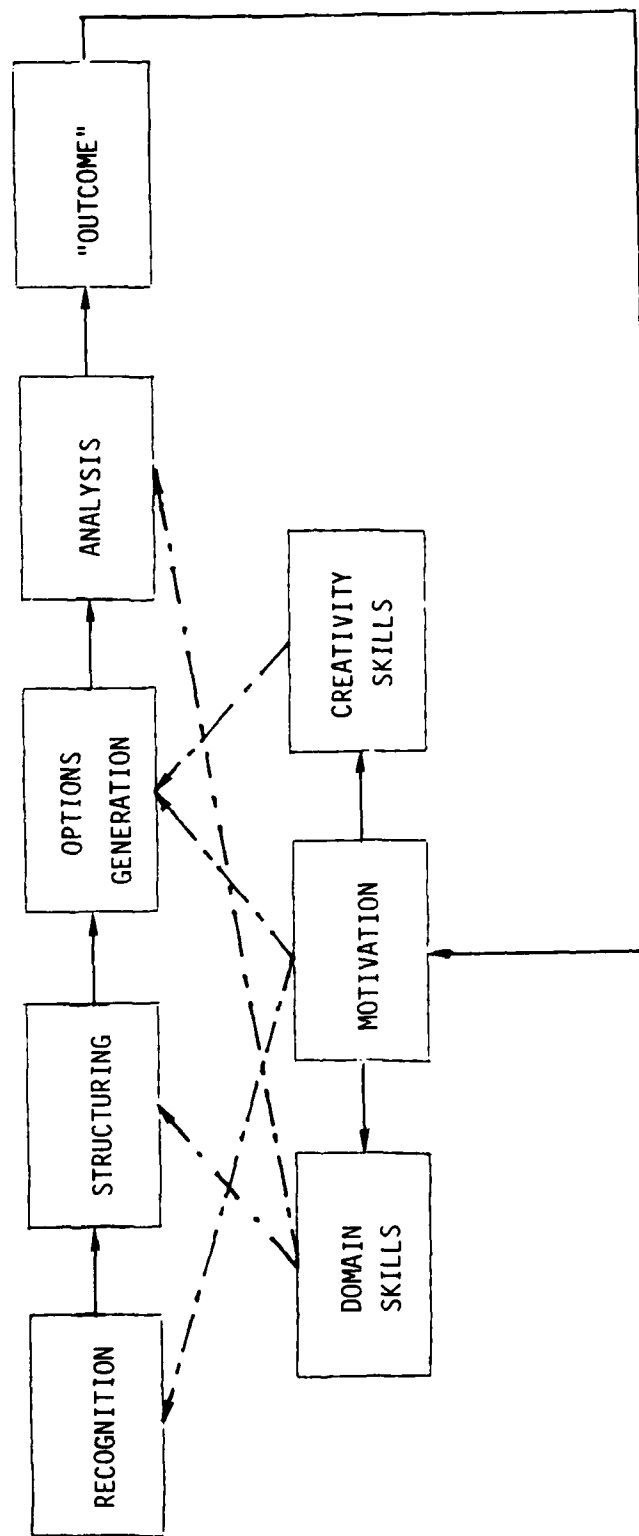


Figure 3.4 Interaction of Process and Componential Models

Unfortunately, the concepts of novelty and feasibility, which are vague even for clearly defined problems, become increasingly imprecise when we attempt to apply them to our typical open problem. Furthermore, the nature of the option generation task is such that we are also interested in the set of options. Thus not only do we concern ourselves with the characteristics of the individual options, but we are also concerned with properties of the ensemble of options. Typically we might be interested in the number of options generated and their breadth of coverage of the major issues in the problem. The main point to make here is that the measurement problem is rather severe. It is naive to imagine that a complex concept can be captured with a single numerical measure. At the very least we need a vector of measures, some components of which can only be subjectively determined. We develop this view in Chapter 6 where we define and use a measuring scheme for option generated by the subjects in our second experiment.

3.4. Cognitive Biases and Styles

In defining our environment we have, so far, considered an abstract model of the decision process, a corresponding task model and a psychological model of creativity. We now focus on cognitive biases and styles as representing one further set of psychological factors that should be taken into account. We ask what impact biases and styles can have, and examine ways in which the environment can be designed to minimize bias effects and enhance the strengths contained in various styles.

While cognitive biases have received much attention from experimental psychologists, our understanding of them is rather limited.

See Kahneman et al [45] for recent views of these issues. So that although we can enumerate a large variety of systematic biases that can occur, we have no theory which tells us if indeed they will occur under any given conditions. This makes it difficult for us to design an environment that will successfully prevent the decision maker from exhibiting them. The best we can do is to be alert for typical situations in which biases are known to occur and then make the decision maker aware that biases may be operating. Specific techniques for bias correction have not been reported, except for some special cases noted by Kahneman and Tversky[44], so the help the environment gives must be of a rather general form.

One way of exploring the potential impact is to categorize biases according to the decision process stages in which they occur. We show, in Table 3.1, a list of commonly known biases organized by process phase. We see that biases that affect the way in which the decision maker reacts to cues in the environment have most impact on the information gathering task. Biases that affect the way in which information is processed have most impact on that part of model building and problem solving which requires inference, reasoning and estimation. Biases that affect the way in which judgements are expressed have most impact on outcome evaluations, and biases that affect the way in which the decision maker gets feedback from the problem environment have most impact on his ability to implement and review the chosen plan.

By doing the categorization this way, we can get some ideas about general environment characteristics. Thus everywhere we know that a bias might exist, we should try to ensure that the environment minimizes the

INFORMATION ACQUISITION	INFORMATION PROCESSING	OUTPUT	FEEDBACK
<ul style="list-style-type: none"> ● Availability ● Selective perception ● Frequency ● Concrete information ● Illusory correlation ● Data presentation 	<ul style="list-style-type: none"> ● Inconsistency ● Conservatism ● Non-linear extrapolation ● Rules-of-thumb ● Anchoring and adjustment ● Representativeness ● Law of small numbers ● Best guess strategy ● Justifiability ● Regression bias ● Complexity ● Emotional stress ● Social pressures ● Consistency of information sources 	<ul style="list-style-type: none"> ● Question format ● Scale effects ● Wishful thinking ● Illusion of control 	<ul style="list-style-type: none"> ● Outcome irrelevant learning structures ● "Gambler's fallacy" ● Success/failure attributions ● Logical fallacies in recall ● Hindsight bias

Table 3.1. Some Common Biases

likelihood that it will actually occur. If the decision maker is searching for information then we should try to make sure he sees everything relevant, not just that which he thinks is relevant. So, for example, if the decision maker is assessing probabilities then we should ensure that he is using base rate information correctly. The question of how we might make such procedures operational is, of course, still open, but we will discuss a possible approach in the final section of this chapter.

In contrast to the widely accepted phenomenon of a cognitive bias, the existence of cognitive (or decision) style is highly contentious. Although the concept of a decision maker having characteristic patterns of behavior within the problem solving context is uncontroversial, the idea that these patterns are rigid and that decision makers fall into well defined categories has met with considerable resistance. See Huber[36] for a good discussion of some of these points, and Zmud[87] for a review of the experimental data. More importantly, there is no real evidence that possession of a specific style in any way helps or hinders the process of decision making. Nor does there appear to be any work that shows, or even attempts to show, correlations between style and biases.

If cognitive style has any impact at all on our concept of an environment, then we believe it to be of only secondary importance. We need to be aware of typical behaviors so that we provide as much flexibility as possible, both in terms of the features in the environment and the way in which the decision maker can interact with them, but we view this as an implementation rather than a design issue.

INFORMATION ACQUISITION	MODEL BUILDING	PROBLEM SOLVING	OUTCOME EVALUATION
<ul style="list-style-type: none"> ● "On-line" database ● Libraries ● Experts 	<ul style="list-style-type: none"> ● AHP ● Influence diagrams ● Templates ● Checklists 	<ul style="list-style-type: none"> ● Analogies ● Free association ● Assumption challenging ● Brainstorming ● Blockbusting 	<ul style="list-style-type: none"> ● Simulation ● Decision analysis ● Sensitivity techniques

Table 3.2. Examples of Tools

While our argument is that the decision maker may require help in performing all these tasks, in our current effort we have concentrated on those in which generic, rather than problem specific, tools are most appropriate. We have, therefore, been mainly concerned with model building and problem solving. The details of our efforts in these areas are given in the following three chapters. The remainder of this section is concerned with giving a survey of the tool categories described above.

Information gathering is, obviously, the task of obtaining knowledge about the problem and its context. The decision maker might make use of a wide range of sources: from computerized data bases to card indexes, from reference books to telephone conversations with experts. All these sources may not be available in the decision maker's immediate physical location, so our concept of environment here is somewhat vague. All that is important is that the decision maker has ready access to the information he feels is relevant. Clearly, the kind of information required is problem dependent and it has not seemed feasible in this study to examine these information requirements in great detail. However, we note that in the business world the supply of information to management through computerized management information systems is seen as an important aid in improving the quality of decision making.

Model building also covers a wide range of activities. It is, however, more amenable to general approaches than is information gathering. Thus there are some general techniques that can be applied without direct reference to the particular problem faced by the decision

maker. In our work on option generation, it has been this issue of model building that has most concerned us. We will elaborate on the reasons for this in the next chapter, but it seemed to us, at least initially, that in complex problems what the decision maker lacks most is the facility for structuring the main elements of the problem.

Tools that might be appropriate in helping the decision maker construct a representation of the problem range from simple check lists to more formal, and elaborate, schemes such as AHP. Of course, each structuring tool has its appropriate use; a checklist might be useful if only a limited amount of time is available, or if the decision maker only needs a preliminary structure for his problem. More elaborate tools require the decision maker to expend greater effort and this may not always be appropriate or convenient.

Tools for problem solving are hard to define since we have no detailed model of this cognitive process. Nonetheless, we do have a qualitative understanding and this can be used to help us construct a variety of potentially useful tools. In doing so it is important to realize that there are several methodologies in existence for improving creativity. Some of the best best known of these are Conceptual Blockbusting[2], Lateral Thinking[10], Brainstorming[57] and Synectics [63], and within them there are some specific procedures which are claimed to improve problem solving ability. The main characteristic of all these techniques is that they attempt to make the problem solver take an unusual view of the problem. They use assumption challenging, unrestricted non-judgemental thinking and reasoning by analogy as ways of aiding the breaking of mind sets. We believe that such devices can

be easily incorporated in the toolbox.

Tools for helping the decision maker perform evaluations of options exist in many forms. Perhaps the most widely known are those in decision analysis. However, in our view of the problem any device that provides information about the likely effect of implementing the options is an outcome evaluator. Thus a computer simulation model would be included in this category, as well as AHP, decision trees and multi-attribute utility methods.

Finally, monitoring tools would include devices for recording the progress of a plan, techniques for detecting deviations from expected paths and methods for deciding how plans should be changed to take account of new information. In our effort, we have not addressed these issues at all. The reason being that we have focussed on the early stages of the decision making process, believing that most insight and progress would be achieved by considering the relatively unexplored issues of structuring and creativity. Also, since we have been constrained to work on generic open problems, rather than specific problem domains, it is natural that we should have avoided exploring tools that need this special domain knowledge.

3.6. A System Architecture for Option Prompting

In this final sub-section we describe a possible computer system architecture that would support our concept of an options prompting environment. This serves two purposes. First, it enables us to draw together the ideas discussed in the earlier sections, and second, it shows how our environment could be made operational. The intention is to

provide just the outline of a system and to indicate how it would be used.

A block diagram of the proposed system is shown in Figure 3.5. It contains five major elements: a user interface, a knowledge base, an executive, an option list, and a toolbox. The last of these is the collection of tools we discussed in the previous section. From the system point of view, the toolbox will also contain simple tutorial material about the tools and their advantages and disadvantages. This allows the decision maker to explore the capabilities of the toolbox if he is unsure of what it contains or needs help in using a specific tool.

The toolbox by itself is not sufficient for us to provide the guidance and help the decision maker actually needs in choosing appropriate tools and overcoming potential biases. To give the environment the desired characteristics, we have to provide a repository for our understanding of typical decision behavior (the knowledge base), a mechanism for utilizing this knowledge (the executive), a device for recording the option structure being developed (the option list), and procedures that allow the decision maker to interact easily with the system (the user interface).

If we think of the environment that we construct as having a persona, then our aim is to simulate an "objective critic". The environment provides help when prompted by the user, but also has the capacity to interject when biases, or potential biases, or inappropriate behavior are detected. Thus the role of the environment is to remain passive so long as the decision maker is satisfied with his progress. When he needs help, the environment should be able to give him advice

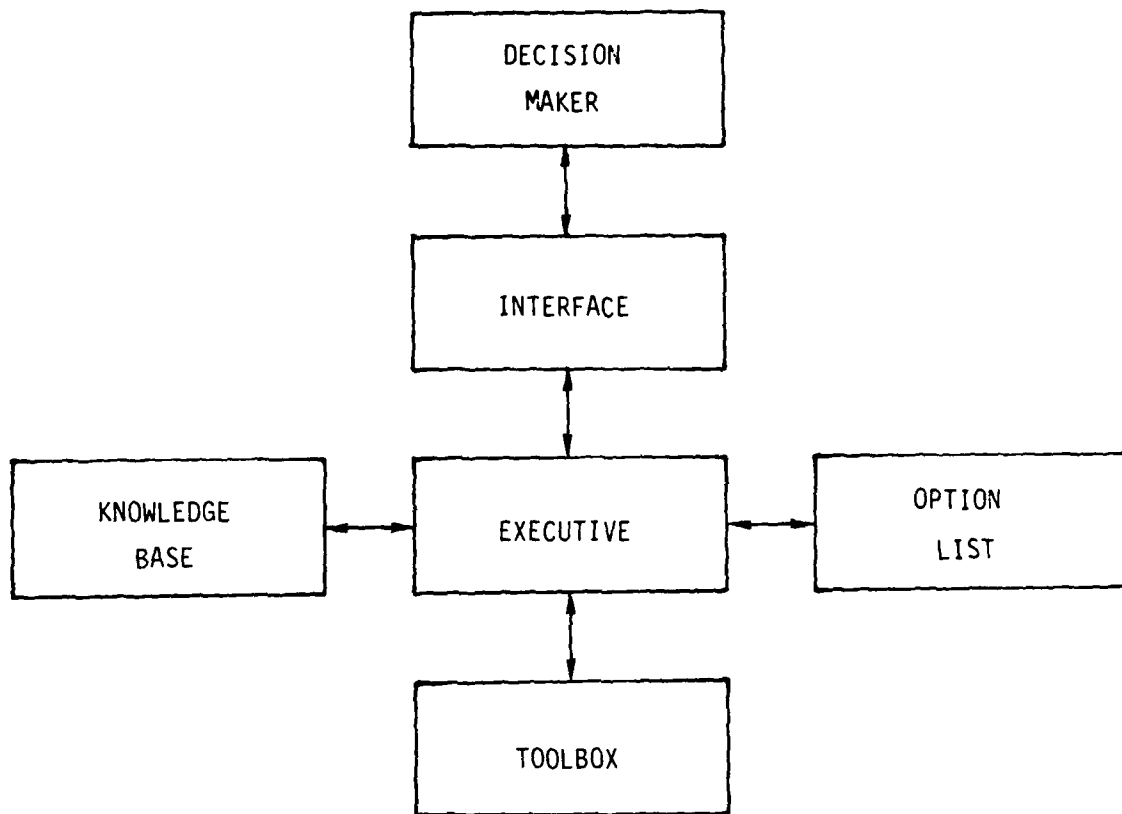


Figure 3.5. An Option Prompting Environment

and point out possible flaws in his current solution set.

The key element in our architecture is the knowledge base. Without it our environment would be entirely passive and not significantly different from a simple toolbox. It is within the knowledge base that we keep our high level knowledge about decision making. This can take many forms; from simple prescriptions for giving responses to "what next" questions from the decision maker, to elaborate procedures for checking whether the decision maker is engaging in unsatisfactory behavior.

The purpose of the executive is to perform all interpretive and housekeeping tasks that are necessary to make the system work. It keeps track of where the decision maker is in relation to his use of the tools, it decodes and acts upon commands given by the user and it generally controls the flow of data in the system.

The idea behind the current option list is that the decision maker needs some mechanism for storing his currently active set of options. This may be a simple list but, more likely, it will have some form of tree structure. The environment will allow the decision maker to record his options in the most appropriate form and provide a simple way of editing them. In its more active mode, the environment may have the ability to detect that the options being generated are merely refinements of existing options. It could then suggest to the decision maker that efforts be made to think of options in other areas. Conversely, if the decision maker has thought of several high-level options but has not begun to explore the details of any of them, then the environment could remind him that this might be a valuable way to proceed. The option list serves two purposes, therefore. It allows the

decision maker to record his ideas, but it also provides a way of telling the environment how the decision maker is progressing. As the decision proceeds, then the option list will become smaller until, at the point of decision, it is reduced to a single entry.

The user interface is, as its name implies, that part of the environment that the decision maker interacts with. Its purpose is to make the process of using the environment as easy and acceptable as possible. The interface will allow the decision maker to have a flexible dialog with the system by utilizing advanced graphics and interactive terminals.

Overall our architecture is designed to provide a decision environment that is supportive, helpful and conducive to generating good solution options to open decision problems. It exists only on paper of course, but we have tried to show what the system requirements are and how these reflect our study of the issues. In the next three chapters of the report we will describe our attempts to explore some of the details of our environment. We discuss a particular form of structuring tool and an experiment designed to test its value, and then describe an experiment that tests a very simple form of environment.

4. THE ANALYTIC HIERARCHY PROCESS FOR DECISION PROBLEM STRUCTURING AND DECISION FACTOR PRIORITIES

In the previous chapter we described the concept of an Option Prompting Environment. One of the underlying motivations for this view of the options generation problem was the belief that decision making is a multistage iterative process. Problem structuring and determining the importance of decision factors were then identified as two important activities that the decision maker could perform to focus on those areas and relationships most likely to lead to new germane alternatives. In this chapter we examine the issues of problem representation and structure, and present Saaty's "Analytic Hierarchy Process" [67] as a powerful aid for helping the decision maker order and analyze the factors that will influence his decision. Appendix C contains a detailed, mathematical description of the AHP.

4.1. Problem Representation

Decision problems often require the decision maker to identify and organize complex sets of goals, actors, constraints, and resources. If some of these are inadvertently ignored, or the relationships between them not properly understood, then potential solutions to the problem may be overlooked. In conventional decision analysis this stage of the decision process is called problem structuring, or issue identification. Its importance is recognized by most decision analysts, with the result that several major software packages have been developed to help the decision maker with this task (e.g., Gulick [27], Humphreys et al [39], Merkhoffer et al [53]). However, in all of these studies there is an

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implicit assumption that the problem can be represented by means of the classical decision tree. This approach presupposes that models with sufficient fidelity to the specific decision can be constructed for each branch of the tree and used to calculate values, which in turn can be used in a procedural way to select the preferred option. However, in complex, novel, open decision situations, it appears that this is an invalid assumption, or at least a considerable amount of effort is required before appropriate models and values can be constructed. Time may not be available.

There is evidence (see [60],[61]) to suggest that, at least in the preliminary stages of problem structuring, decision makers would achieve a better understanding by concentrating on their own goals and other major determinants in the problem, rather than by trying to develop a formal time evolving sequence of action/outcome alternatives. Indeed, Pearl et al [59] use exactly this argument to justify their development of a structuring aid that helps the decision maker develop a tree of goals and sub-goals.

Saaty [67] notes that significant factors may be left out because of simplifying assumptions needed to make the quantitative models tractable. He states, "To be realistic, our models must include and measure all important tangible and intangible, quantitatively measurable, and qualitative factors." The AHP provides the mechanisms for doing this. Saaty provided a program for the mathematics of the analytic assessment of priorities. AI&DS has extended this program to also help facilitate construction of an appropriate hierarchy model for the decision problem.

Within the context of the Option Prompting Environment discussed in the last chapter, the toolbox should contain a selection of tools for problem structuring and evaluation. The specific tool(s) selected by the decision maker will be specific decision problem dependent. We believe that focusing on goals, actors, constraints, and resources is a very general paradigm that can be applied to many decision situations. We further believe that AHP is a very flexible and powerful tool for making this paradigm operational.

4.2. The Analytic Hierarchy Process

There are two major activities involved in using the AHP: problem structuring and decision factor prioritization. Each of these subprocesses can be accomplished to varying degrees of detail and accuracy, depending on the decision maker's desires, time, and analysis resources available. The problem structuring results in a multilevel hierarchy of the decision factors, each of which can be quantitative or qualitative in nature. Prioritization of the decision factors results in an assessment of the importance of each of the decision factors, both with respect to the overall goal of the decision, and with respect to other related decision factors in an adjacent level of the hierarchy (i.e., the other decision factors that a given decision factor is most likely to directly affect).

4.2.1. Decision problem structuring

When confronted with a complex situation that requires understanding and a decision, a decision maker is likely first to gain an intuitive understanding of the situation, and then perhaps proceed

toward a more quantitative model of appropriate parts of the situation. A mechanism for gaining an understanding of the decision situation is through the construction of a hierarchy containing all the elements, or decision factors, arranged in appropriate groupings, i.e., levels of the hierarchy.

There are several mechanisms for constructing a hierarchy that represents a "soft" model of the decision situation. Saaty [67] believes there is an innate method of the human mind that groups a list of elements which comprise a complex situation into groups, according to whether they share certain properties. The common properties identifying one level of the hierarchy (group of elements) can be taken as the elements of a new level in the system. This grouping process can be recursively applied until we reach either the single "top" element (which is often the overall goal of the decision process) or the "bottom" level of basic ingredients of the decision process (which are often identified as the resources that can be controlled). This process results in the elements in adjacent levels being related through the defining properties for the levels. This set of relationships represents and the constructed hierarchy provide structure for the problem. In practice, this structure serves as a vehicle for analyzing the functions of the systems within the decision situation.

Saaty [67] has applied this hierarchical structuring (modeling) process in several application domains and presents generic formats for the different types of domains. For high level modeling of (military) conflict situations we believe the generic hierarchy template of Figure 4.1 is appropriate. (The identifying descriptors for each level of the

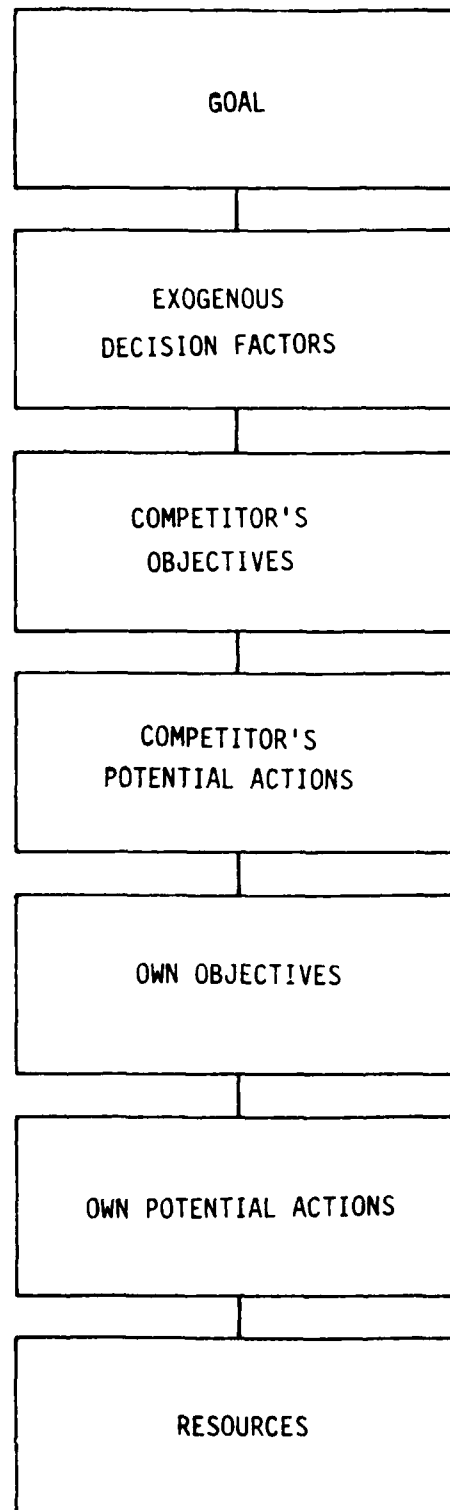


Figure 4.1 Generic Hierarchy (Template)

hierarchy imply the types of elements that would be put into that level.)

During the contract the intent has been to stay as generic as possible. Hence the above template is quite abstract. For a specific class of decision makers we believe it is possible to subdivide the space of all types of decisions that they are likely to face, into a small number (on the order of 10) of subsets. The decision process would be similar for all decisions within any one subset. Thus a specific decision situation for each subset could be chosen and a specific, more detailed hierarchy could be constructed. The decision maker confronting his own specific decision situation could select the appropriate template for his type of decision, and using reasoning by analogy, modify the template hierarchy to better fit his own problem. Robinson [66] and Kelley et al [46] have already given some attention to templating for decision problems. Artificial Intelligence techniques could be used to help select the right template and then aid the decision maker in appropriately modifying it for his specific decision situation.

For purposes of option generation the hierarchy structure required for the AHP has several advantages:

- (1) It provides a mechanism for quickly estimating the scope of the effort that should be involved in making the decision and a road map of the elements that deserve at least some attention. This may help keep the decision maker(s) from "locking on" one specific aspect of the problem for too long, to the detriment of exploring other areas.

- (2) It provides a "soft" model whose structure can be easily changed to explore different concepts.
- (3) It provides a good vehicle for focusing communication among various decision makers and staff.
- (4) It provides a good mechanism for ensuring an early common understanding of terms and concepts.
- (5) It fosters and orders discussion of (thinking of) potential variations on the baseline decision situation.
- (6) It combines quantitative and qualitative factors into a single structure.

A major disadvantage of this structure is that for some people it does not have sufficient cause and effect relationships explicitly defined, i.e., the model is not sufficiently well defined for them.

4.2.2. Analytic decision factor prioritization

The second major subprocess of the AHP is determining the priorities among decision factors at each level of the constructed hierarchy. The specific process is delineated in detail in Appendix C. Both global priorities (with respect to the overall goal) and local priorities (with respect to decision factors in the level immediately above the level of the hierarchy under current consideration) are obtained. The raw input used to obtain these priorities is a sequence of pair-wise comparisons between decision factors with respect to another factor in the next higher level of the hierarchy -- a factor related directly through the defining properties of the level to the two decision factors being compared. Decision maker(s)/staff tend to be

willing to make these pair-wise comparisons much more readily than global or local ordering of a list of elements.

An important point for fostering option generation with decision maker(s)/staff is the mental process they use in making their pair-wise comparison estimates. They typically think of a myriad of scenario variations to arrive at their estimates. As they move from one pair-wise comparison to the next, they continually rethink many of these scenario situations from different perspectives. This quick repeated consideration leads to identifying why factors are more or less important and provides some insight into what conditions/parameters they are sensitive to. Thus, they not only get an analytic assessment of the priorities of various decision factors, but gain insight into specifically why and into how robust or sensitive to change they are.

We felt that understanding the sensitivity to change and to anomalies within the basic scenarios considered would be conducive to generating new options. During the contract the basic AHP theory was extended to more formally make evaluations of sensitivity impacts; these extensions are also presented in Appendix C. However, they were not incorporated in the AHP package the subjects used in the experiments reported in the next two chapters.

Major disadvantages of the prioritization process for the creative task of options generation is that it becomes tedious, and perhaps too repetitive in nature, for large hierarchies. In the current form the entire process must be completed in a definite order before any global priorities are produced.

A major payoff for option generation after the entire process is completed is that the most important decision factors are indicated and time and effort can be focussed into those areas and away from the lower valued factors.

5. THE MONTEREY EXPERIMENT

In the previous chapter we described the Analytic Hierarchy Process (AHP) and discussed its possible use as a tool for helping decision maker's structure their thinking about decision problems and evaluate the relative importance of decision factors. Accordingly, our first experimental investigation was designed to evaluate the concept that these two AHP supported processes would help the decision maker generate options. At the same time, we were concerned to confront, and learn about, the difficulties inherent in performing experimental research in this area. A more detailed report of the experiment and its results can be found in Tong[75].

Since we view Option Generation as essentially a creative task we are faced with several dilemmas. We must first determine to what extent people are naturally creative when faced with a difficult problem. Clearly, understanding normal unaided behavior is a pre-requisite to the development of devices that can improve on this behavior. One goal of our first experiment, therefore, was to determine exactly what kinds of options would be generated.

A second dilemma is how to introduce the aid in a manner that supplements the decision maker's normal behavior. In particular, we need to guard against the possibility that presenting the decision maker with an aid will actually inhibit his performance. When providing subjects with aids that run as computer programs, it is important to develop experimental methods that overcome the subjects' potential difficulties with the new technology.

A third difficulty is to define the idea of a good option in a sufficiently precise manner so that the performance of the subjects in an experiment can be measured and evaluated. Each problem has many possible solutions that may be presented at many different levels of detail. Determining qualities such as the adequacy and creativity of options is a severe measurement problem.

5.1. Experimental Method

A group of sixteen students enrolled in the Command and Control Curricula at the U.S. Navy Postgraduate School (NPS) in Monterey were subjects for our experiment. We divided them into two groups of eight, attempting to match the groups in terms of service background and rank. That is, we tried as nearly as possible to have an equal number of Navy, Air Force and Army personnel in each group, and the same number of Major/Lieutenant Commanders and Captain/Lieutenants in each group. Our reasoning being that service training and background should have an influence on a subject's ability to deal with the problem scenarios we were to present. By partitioning the subjects in this way we avoid a potential bias in the results.

The experiment took place over two days at the NPS. Access to the AHP aid was provided over the ARPANET using the computer facilities in the School's C³I Laboratory. The experiment was an A-B, B'-A design, with all subjects being in a control condition (A) and a treatment condition (B or B'). Thus on Day 1 half the subjects were in condition A and half in condition B. On Day 2 they changed round being in conditions B' and A respectively. The treatment condition on both days involved use of the AHP aid, but the subject's interaction with it was

different on the two days.

We used two problem scenarios: a "Downed B-52" on Day 1, see Figure 5.1, and a "War Game" on Day 2, see Figure 5.2. These are primarily military but have political implications. Both groups attended a brief verbal introduction to the problem, were given the stimulus material we prepared (instructions and supplementary material such as maps) and were then allowed two hours to generate options to solve the problem.

On both days, the subjects in the control group worked individually and were asked to write down as many creative options as they could. Each option was to be written on a separate sheet of paper with no constraints on the format.

On the first day, the subjects in the treatment group worked individually with the AHP aid. They were given some preliminary guidance in its use, but were then expected to interact with the aid via a standard alpha-numeric computer terminal to help produce their own written options. Assistance with the technical aspects of the aid was available to them throughout the two hour period.

On the second day our presentation of the AHP aid to the treatment group was different. We found that on the first day the subjects had difficulty using the AHP aid because they were not familiar with the computer protocols needed to interact with it. To overcome this, we conducted a group session with one of us acting as mediator and another one of us as interface to the AHP aid. The subjects thus structured the problem as a group, but then worked individually to produce their written options.

A fully armed B-52, equipped with the latest penetration aids, is on a routine peacetime mission at the Eastern end of the Aleutian Islands. His mission profile was to take him close to Soviet territory near the Commander Islands, and then generally Southwest, parallel to the Kuril Islands.

At 1045 (local time), 23 January, the B-52 reports a failed generator, but that the mission is being continued. At 1510, a Pan American jetliner, nominally on a great circle route from Seattle to Tokyo, reports on the International traffic control net that he has received a crash beacon signal from an area near the Eastern most Islands in the Commander Islands, with a large associated area of uncertainty.

All subsequent attempts to contact the B-52 are futile.

There is ice around the Commander Islands. Current weather reports scattered clouds at 3,000 feet and 20,000 feet, and forecast to remain the same for 24 hours.

A Soviet Naval Surface Combatant Task Group is on maneuvers 400 nautical miles to the Southwest.

A Japanese fishing trawler is 250 nautical miles South of Attu Island.

All U.S. military and coast guard assets are conducting their "normal" peacetime activities.

What should be done?

Figure 5.1 Day 1 Problem Scenario

Grey and Orange governments have been ideologically opposed and hostile toward each other for a long time. Grey's military capability has diminished during the past few years. An appreciable segment of the population in Eastern Grey are sympathetic with Orange. Insurgency by these "Grey Eagles," logistically supported by Orange, has resulted in their de-facto control of the Eastern-most area of Grey, except that Grey still controls and operates SMALL AIRPORT. Recent Grey Eagle successes encourage Orange to actively enter the struggle. They capture SMALL AIRPORT and immediately start enlarging it.

Grey appealed to the UN for aid.

Blue has previously indicated that any Orange overt use of force in Grey was unacceptable, and asked for congressional approval for unilateral support of Grey if favorable UN reaction was not immediate. Purple concurs with Blue.

Blue has a Tactical Air Wing stationed in air bases in Purple, within range of SMALL AIRPORT. The Wing Commander is given the mission: "When directed, begin operations to neutralize Orange forces and facilities in Grey. Do not attack targets in Orange. Take defensive measures to protect your force from Orange or Red retaliations."

No immediate political resolutions are made in the UN or Blue.

Orange completes a hasty enlargement of SMALL AIRPORT. On 1-2 May 3 squadrons of Orange MIG-21 and 3 squadrons of Orange SU-7 attack aircraft arrive at SMALL AIRPORT.

At 2300, 2 May, the Wing Commander is directed to execute this assigned mission. The first reconnaissance flight on 3 May reveals the presence of several air defense missile sites and 3 Red Hospital Aircraft, with large Red Crosses, parked near Orange's aircraft and the runway at SMALL AIRPORT.

What does the Wing Commander do to execute his mission?

Figure 5.2 Day 2 Problem Scenario

At the end of each day's session, the subjects in the treatment group were asked to complete a questionnaire. The responses were used to assess the acceptability of the aid. The subjects in the control group were asked for their verbal impressions of the experimental procedure.

5.2. Results and Commentary

Our goals in this pilot experiment may be broadly stated as:

- (1) To gain insight into the concept of an option and how this depends on experience and training,
- (2) To form some estimates of the value of the AHP aid as a device for helping options generation, and
- (3) To learn how to perform an experiment that attempts to evaluate a decision aid.

The data we collected allows us to form some subjective conclusions on each of these, and we present them in turn.

5.2.1. Conceptual issues

One of our major concerns was to understand what constitutes an option, and how this depends on the decision-maker and the particular decision problem. In general, we found that there was little variation between subjects and that options were typically very brief. A common structure for the design of options was to list several elements of the problem, two or three approaches to solving each element, and then to generate a string of options by permuting these solutions. While this led to significant numbers of options, this kind of an approach does not

lead to much variability or differences between the options themselves. Thus, for all of the subjects, an option is basically a combination of primitive action alternatives.

Perhaps this is not too surprising given the relatively simple scenarios we used, but the similarity of responses is quite striking. The main differences between options seems to be one of detail. Thus all the subjects on Day 1 realized that before any action options could be generated it was necessary to locate the B-52 and determine the status of the equipment and crew. There were, however, many different solutions to the reconnaissance problem: long range photo-reconnaissance aircraft, satellite sensors, Navy task force, etc. Similarly, on Day 2 all subjects discussed the option of bombing Small Airport, but described different combinations of equipment and munitions for achieving this.

Although there was considerable consistency about the nature of an option, there were very large individual variations in the number and quality of the options generated. On both days, these ranged from the briefest of one-line descriptions to relatively detailed analysis of the problem and possible options. Overall though, the military options tended to be more comprehensive than the non-military ones. Our general impression is that there is as much variation within experimental groups as between them. We attribute this to individual differences in background and training, rather than the conditions imposed by the experiment.

The overall structure of the option sets for the two scenarios was also quite different. For Scenario 1, the options were conditioned upon

the supposed fate of the aircraft and the key to generating a rich set of options was to consider many possible states-of-the-world. For Scenario 2, the key was to interpret the word "neutralize" as broadly as possible. Thus in the first case, creative options came from an ability to imagine the situation in a variety of ways. In the second case they came from flexibility in understanding what could limit the enemy's activity.

Although difficult to quantify, we feel that the options generated for Scenario 1 were more numerous and creative than those generated for Scenario 2. We believe this is because Scenario 1 was well outside the experience of most subjects, causing them to view the problem as something novel and requiring ingenuity. Scenario 2, on the other hand, seems to have been regarded as something familiar, so that fairly standard solutions could be applied.

In summary, the subjects in this experiment perceived an option as a combination of activities designed to address the basic parts of the overall problem. On Day 1 particularly, the options had a dominant time dependent element and took on the character of a plan. There appeared to be little quantitative difference between the treatment and control groups in either the concept of an option or the level at which it was described. The variations that do appear are probably best attributed to individual subject differences rather than the experimental conditions.

5.2.2. The value of AHP

Our original thinking about the characteristics of an aid led us to believe that the Analytic Hierarchy Process had features that would be of benefit in Option Generation. Having developed an interactive computer-based aid that allows the user to construct and prioritize a hierarchy of decision factors for the problem, one of our goals was to determine if this aid would be of benefit to the subjects in our experiment.

Unfortunately, the procedural difficulties that the subjects experienced were quite severe. On Day 1 most ran out of time, being more concerned with the mechanics of hierarchy construction and prioritization than with the actual Option Generation task. On Day 2, we attempted to alleviate this difficulty by conducting a group exercise in construction and prioritization. However, time was still a significant factor and forced a premature termination of the prioritization. Consequently, our comments on the apparent value of the AHP aid must be conditioned on this important constraint.

If we compare the options generated by the control and treatment groups on both days, it is clear that control group responses are generally more detailed and numerous. We believe this negative result to be primarily due to the procedural problems (a view supported by our second experiment, see Chapter 6) and so have not attempted a quantitative analysis of the options generated. Instead, we have formed a set of subjective impressions that we elaborate below.

There is some evidence that the range of options generated by the treatment group on Day 2 is greater than that of the control group. Our

subjective interpretation is that Scenario 2 seemed very familiar, causing the control group to think mainly in terms of destroying Small Airport. The treatment group more often considered options like blockades and further diplomatic activity, prompted, presumably, by the broader view of the problem that the hierarchical structuring and prioritization gives.

These tentative conclusions are supported by a reading of the questionnaires returned by the treatment groups. On Day 1 the responses had a negative tone, although half the subjects thought that the procedure helped them to be more analytic, with the other half unsure. Most subjects on Day 1 were comfortable with the pairwise comparison technique, but some commented that for large hierarchies this process becomes very tedious. The response to the value of the priorities were very mixed. Several subjects were unable to answer because they did not complete the prioritization. Others felt them useful only in the sense that they identified the most dominant factors. That is, the ordering was more important than the absolute values of the weights. Still others said they ignored them.

On Day 2, the subjects felt much more positive towards the AHP process. All but one of them found the pairwise comparison process to be useful. Several also found the priorities to be of value, although many more were either unsure or offered no comment.

On balance then, the structuring aspects of the AHP aid seems to have been received favorably and perceived as useful by the subjects. The value of priorities seems to be limited however. As a comment, it is characteristic of the AHP that both hierarchical structuring and

prioritization have to be completed before the full power of the aid can be realized, and in limited time decisions it may not be possible to do this. Sufficient training in the use of AHP would tend to alleviate, but not negate, this problem.

There is little evidence to suggest that creativity is enhanced by AHP. Indeed several subjects made comments to the effect that while the structuring exercise increases understanding, there is a possibility that the hierarchy restricts creativity by forcing the decision maker to accept a static relationship between the decision factors.

In summary, the data generated by this experiment does not allow us to draw any quantitative conclusions about AHP. However, we can see clearly that it has value as a tool for analyzing the structure of problems. On the other hand, it is a relatively complex procedure and requires the decision maker to commit a substantial amount of effort before its value can be realized. A more flexible and robust version of the software would help alleviate some of these problems, but in restricted time situations we should expect its effectiveness to be reduced.

5.2.3. Procedural issues

Perhaps the main lesson learned from this experiment is that performing an experiment that attempts to assess the value of a decision aid in a complex decision situation is distinctly non-trivial. In this section we will highlight some of the more important issues.

First, it is vital that the subjects practice with the aid before they are asked to use it under experimental conditions. When the aid is

a complex computer program, there is a significant learning period during which the user overcomes his preoccupation with the procedural questions. We estimate that the user needs several exposures to AHP, both the theory and the practice, before we could expect him to be confident enough to apply it to a real problem, in such a way that he uses most of his energy thinking about the problem rather than about using the tool.

Second, it is important to make sure that the subjects understand exactly what is required of them. They need clear instructions and unambiguous definitions. Scenario 2, in particular, caused some confusion. The description, we thought, clearly emphasizes that the Wing Commander is the decision-maker asked to generate the options. Yet many subjects offered options available only at a much higher level (for example, pursuing various diplomatic activities).

Finally, while the Debriefing Questionnaire was well structured and allowed us to compare responses, the decision to allow a free format for the options themselves considerably hampered our ability to derive any quantitative results. There was considerable variation in style and presentation, making the analysis of individual responses very time consuming and error prone.

5.3. Summary

In our search for ways of aiding decision-makers in the task of Option Generation, we identified the Analytic Hierarchy Process as potentially useful, and in this Chapter we have described an experiment to test its value. Other important goals were to refine our

understanding of the concept of an option and to assess the problems associated with performing experiments of this kind.

The data we collected during the experiment has allowed us to draw some strong procedural conclusions but rather weak theoretical ones. As a result we have only been able to assess the value of AHP concept in a very preliminary way.

Briefly, the lessons are:

- (1) Group use of AHP with a mediator appears more satisfactory than individual use.
- (2) Hierarchical structuring of the problem does help problem understanding, but we found no evidence that the overall AHP procedure helps generate creative options.
- (3) An option is a combination of primitive action alternatives, with time dependence of actions often made explicit.
- (4) Individual experience appears to be a dominant factor in determining the richness of the options generated.
- (5) It is most important that subjects are given adequate time to familiarize themselves with the aid.
- (6) It is important to provide clear experimental instructions.
- (7) Assessment of free form written responses is very hard. While there is a danger of unduly constraining the subjects, more structured responses are necessary if meaningful quantitative analysis is to be performed.

6. THE STANFORD EXPERIMENT

An important goal of this experiment was to test a simple version of our Option Prompting Environment. This consisted of a collection of aids from which subjects were free to select as many or as few as they wished, and at whatever time they wished. We attempted to provide a broad selection of problem solving aids, including information about the problem, aids for structuring the problem, and creativity aids. The information packet was specific to the problem, whereas the structuring and creativity aids were quite general. The structuring aids were designed to broaden the subjects' conception of the problem. One aid was a simple checklist, which urged subjects to consider the political, social and economic factors of the problem. A second structuring aid was a problem solving template, which required subjects to generate a matrix of issues important to the problem. The actual template consisted of a matrix of boxes, to be filled in with a list of the actors, each actor's goals, resources, and constraints, and any possible environmental factors which would figure in the problem. The creativity aids were designed to help the subjects "break set" (Luchins [50]), and shift their understanding of the problem, or shift to a new area of possible solutions. Included in the creativity packet was an exercise which asked subjects to list the assumptions they had about the problem, and write down a negation of the assumption. Another exercise listed a variety of "brainstorming" questions (Osborne [57]; Gordon [26]). A third exercise listed a set of unusual words, and asked for the subject's free associations to those words. A subject who had spent

some time generating very similar options would be forced to use a different area in semantic memory during the free association exercise, and therefore think of solutions slanted toward a different aspect of the problem.

We also re-tested the effectiveness of the Analytic Hierarchy Process (AHP). We hypothesized that the computer implementation of AHP would motivate subjects to develop a broad conception of the problem, and to understand the relationships among elements of the problem. Such an understanding appears particularly important for open problems, in which the problem structure is neither obvious nor predefined.

A major difficulty of evaluating problem solving and creativity aids is the issue of measurement. The concept of a good option or a good set of options is ill-defined, and may vary across situations. Thus, an important aspect of the experiment was the development of a set of measures of option generation performance.

We hypothesized that cognitive style might mediate the usefulness of problem solving aids. For example, some people may already possess effective strategies for problem solving. External problem-solving aids might hinder the use of these subjects' own strategies, and produce poorer performance. On the other hand, people who are relatively uncreative, or who have difficulty structuring problems might benefit more from our problem-solving aids. We used two tests of cognitive style in an exploratory manner. The first was the Embedded Figures Test [84], which divides subjects into field dependent versus field independent. Field independence versus dependence maps onto the divergent versus convergent thinking dimension. People who are field

independent tend to be divergent thinkers, which is supposedly typified by fluid and flexible thinking. Field dependent people tend to be higher on convergent thinking. Therefore, the problem solving aids may be more useful for the field dependent subjects. The second test of cognitive style was the attention subtest of the Test of Attentional and Interpersonal Style (Niedeffler [56]) which measures variations in the direction and general breadth of attention.

6.1. Experimental Method

Thirty Stanford University students were obtained as subjects through signs requesting volunteers for an experiment in problem solving.

We wished to test the problem solving aids on an open. real-life problem. Furthermore, we wanted to choose a problem which subjects would be motivated to solve, and about which they had a large store of domain relevant knowledge. (Perceived lack of domain knowledge has been indicated as a block to options generation in comments by several subjects in the Monterey experiment.) After pre-testing several problems, we chose the problem of campus security in response to a recent series of attacks on women at Stanford. Since all subjects were students on the Stanford campus, they had a great deal of information about the physical setting, the people involved, and their various goals, resources, and constraints. The attacks were an important and visible issue on campus at the time the experiment was run, and subjects appeared to be highly motivated when generating options.

The ten subjects in the control condition worked on the problem unaided. The ten subjects in the Simple Environment condition were provided with a packet of information about the problem, a set of structuring tools, and a set of creativity tools. The ten subjects in the AHP condition were first trained in the use of a computer aided version of the Analytic Hierarchy Process, and then were allowed to use AHP while working on the problem. Subjects were tested individually.

All subjects read a description of the problem, including information about the attacks, and steps the university had taken in response. Subjects were asked to play the role of a member of a university advisory committee, and attempt to generate solutions to the problem. Subjects then wrote a description of the problem in their own words. They were then asked to list all initial options, which were defined as ideas they had about the problem before entering the experiment. Finally, subjects were given a maximum of two and a half hours to generate new options to the problem. They were instructed to list every idea which occurred to them, without editing ideas which they thought were "silly" or infeasible. Subjects were allowed to stop the experiment at any point.

6.1.1. AHP Condition

One or two days prior to the experiment, people in the AHP session were given a three hour training session on a computer implementation of the Analytic Hierarchy Process. Each subject heard a short lecture-demonstration, and used AHP while working on a practice problem. During the actual experiment, AHP subjects were given access to AHP, with instructions to use it to help generate new options. The instructions

stressed that the main goal of the experimental session was to generate new options regarding the problem, rather than focusing on an exhaustive use of the AHP program.

6.1.2. Simple Environment Condition

People in the Simple Environment condition were provided with three different aids, an information packet, a structuring packet, and a creativity packet. The information packet contained a copy of a newspaper interview with two of the victims, a letter from the chief of police to the community detailing the University response to the attacks, a description of the campus escort service including hours of operation, and a map of the campus. The structuring packet contained a simple checklist, which reminded subjects to consider the economic, political, and social aspects of the problem. A second structuring aid was the template. The template consisted of a 5 by 7 matrix of boxes labeled "Actors", "Goals", "Resources", "Constraints", and "Environmental Factors". An example of a completed template for a different problem (eradication of the Mediterranean Fruit Fly in California) was included as a guide. The creativity packet contained three exercises. The first was a list of "brainstorming" questions, similar to those described in Gordon's book, Synectics. The second exercise was designed to encourage free association. The free association exercise provided subjects with a list of 20 words, and asked them to write down the first word which occurred to them as they read each one. The challenge assumptions protocol asked people to write down any assumptions they had about the problem, and then write down the negation of their assumption, stated in a positive manner.

6.1.3. Control Condition

Subjects in the Control Condition were simply provided with worksheets for recording their options. They were not provided with any problem solving aids.

6.1.4. Post-Experimental Tests

After giving the instructions, the experimenter left the room. The subjects were allowed to work on the problem until they felt they had exhausted their options, or for a maximum of two and a half hours. At the end of the session, the experimenter returned and gave each subject two tests of cognitive style. The Attention Subtest of the Test of Attentional and Interpersonal Style (TAIS) consisted of 75 multiple choice questions designed to divide subjects along two dimensions: direction of attention (internal versus external) and breadth of attention (broad versus narrow focus). The Embedded Figures Test consists of 12 geometric figures with simpler figures embedded in them. Subjects are timed as they attempt to find and trace the embedded figure. People who attain low scores of total time are relatively field-independent. They readily separate objects or ideas from the surrounding context. People with high scores on the Embedded Figures Test are relatively field-dependent, and have difficulty separating objects or ideas from the background in which they are embedded. After the cognitive style tests, subjects in the AHP condition and Simple Environment condition were given a questionnaire about the problem solving aids. Finally, all subjects were debriefed as to the nature of the experiment.

6.1.5. Evaluation of Options

The solutions to the problems were evaluated along a number of dimensions. The first dimension was the number of options generated by each person. A second dimension was the breadth of those options. Based on pilot work with the problem, a list of 13 mutually exclusive, comprehensive categories of options was devised (see Table 6.1). For example, one category included anything which required physical changes to campus, another category included all suggestions of care for victims, and a third category consisted of all options which related to escorts. The options for each subject were sorted into the 13 categories by a judge who was blind to the subject's condition, and the number of categories which contained an entry constituted the subject's breadth score.

Each option was also rated in terms of novelty, feasibility and benefit. Novelty was defined as the degree to which an option was new or unusual. Feasibility was defined as the combined dollar and psychological costs of implementing an option. Benefit was defined as the degree to which an option would alleviate the overall problem. A comprehensive list of all options generated by subjects in the experiment was assembled. Four judges then rated each option on each of the three dimensions. The judges used a separate 0 to 100 scale for novelty, feasibility, and benefit. Two anchor points for each scale were chosen by consensus prior to the judges assessment of all the options. The mean score of the four judges was computed for each option's novelty, feasibility, and benefit score. Then the total novelty, feasibility and benefit scores for each subject was computed by

1. Victim Care
2. Personal Self-defense
3. Classes in Self-defense
4. Personal publicity and education
5. Group publicity and education
6. Physical Changes to campus
7. Rules of behavior or restrictions
8. Escorts
9. Victim Counseling
10. Society: Changes in law
11. Society: Changes in attitudes
12. Police Action
13. Other

Table 6.1 Categories of Options

adding the scores of all the options in that subject's options set. Finally, the average novelty, feasibility and benefit score was computed for each subject.

6.2. Results

A separate one-way analysis of variance was performed on each of the measures: number of options, breadth, novelty, feasibility, and benefit. The results are shown in Table 6.2. Subjects in the Simple Environment and AHP conditions did not differ from the control group in the average benefit, feasibility or novelty of the options they generated. There was also no difference between the treatment conditions and the control group in the number of options generated. However, both the treatment groups generated a greater breadth of options than did the control group subjects. Subjects could generate options in as many as 13 categories. Subjects in the AHP group had an average breadth score of 8.7 categories, subjects in the Simple Environment group had an average breadth score of 7.7 categories, whereas control group subjects had an average breadth score of 6.2 categories ($F[2,27]=6.92$, $p<0.005$). Separate t-test comparisons revealed that while the AHP group and the Simple Environment group were not significantly different in terms of the breadth scores, both were significantly different from the control group.

Subjects were free to spend up to 150 minutes on the problem. Subjects differed significantly in the time spent on the problem across the three conditions ($F[2,27]=3.60$, $p<0.05$). Subjects in the AHP condition spent significantly more time on the problem (154.5 minutes) than subjects in either the Simple Environment condition (106.2) or the

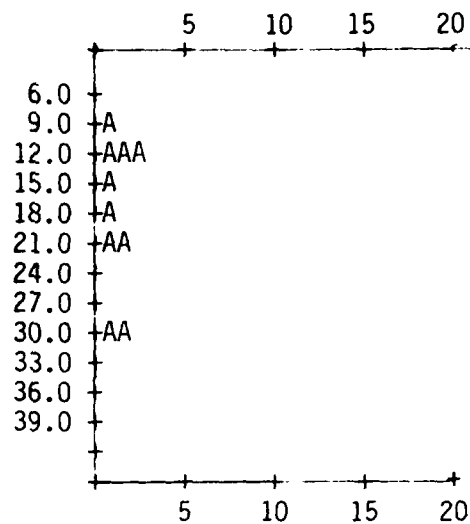
GROUP	DEPENDENT MEASURE					
	NUMBER	BREADTH	NOVELTY	FEASIBILITY	BENEFIT	TIME
SIMPLE ENVIRONMENT	17.0	7.7	23.11	50.14	29.42	106.2
AHP GROUP	19.0	8.7	24.92	44.70	30.54	134.5
CONTROL GROUP	15.2	6.2	23.79	54.09	28.19	99.5
F STATISTIC 2, 27 df	F= .59	F=6.92 p < .01	F=.19	F=1.89	F=.25	F=3.60 p < .05

Table 6.2 Statistics for Treatments

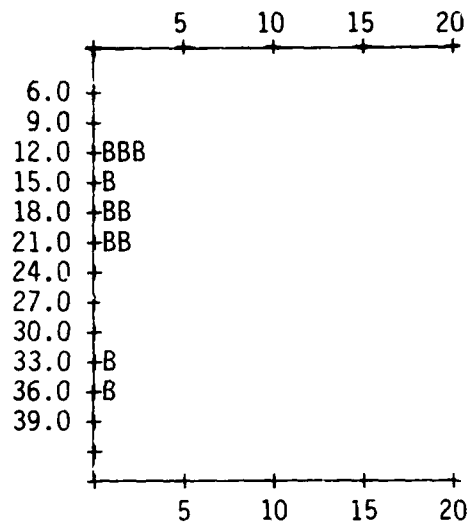
control condition (99.5). The difference may be due simply to the time consuming nature of the AHP procedure. In that case, however, it is interesting that working through the Analytic Hierarchy Process, or using any of the packets in the Simple Environment conditions did not hinder the performance of subjects in those conditions. An alternative possibility is that the treatments may have made the problem session more interesting or perhaps less frustrating relative to the experience of the control group, and thus subjects were more willing to work on the problem.

Figures 6.1 - 6.5 are histograms of subject averaged scores on each of our five measures of "goodness": number, breadth, novelty, feasibility and benefit. The vertical axes show the upper end points of each interval used in constructing the histograms. Thus in Figure 6.1 we can see that only one subject in the Simple Environment group generated less than or equal to 9.0 options, and three generated more than 9.0 but less than or equal to 12.0. Since we have so few subjects in each group the comments that follow on the differences between histograms are necessarily qualitative and should be treated with some caution. We are looking for effects that would be worth exploring in a more extensive experiment. All the histograms show substantial variation within groups emphasizing that there are large differences within the subject population.

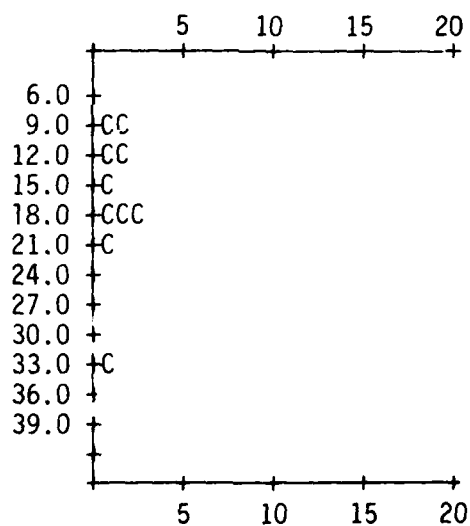
The number scores are shown in Figure 6.1. Notice that all three groups have most subjects generating about 15 options with just a few generating significantly more. The breadth scores are shown in Figure 6.2 and reflect the overall group differences discussed above. As shown



SIMPLE ENVIRONMENT



AHP



CONTROL

Figure 6.1. Histograms for NUMBER scores

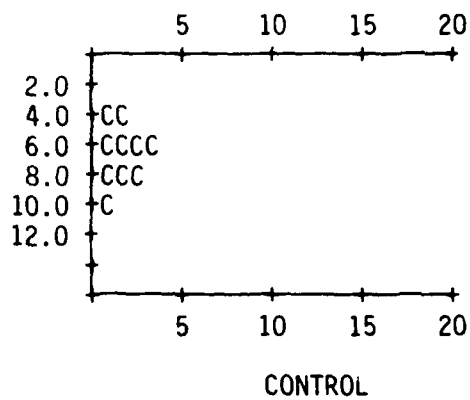
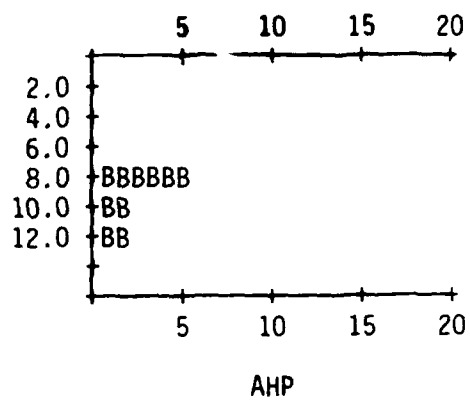
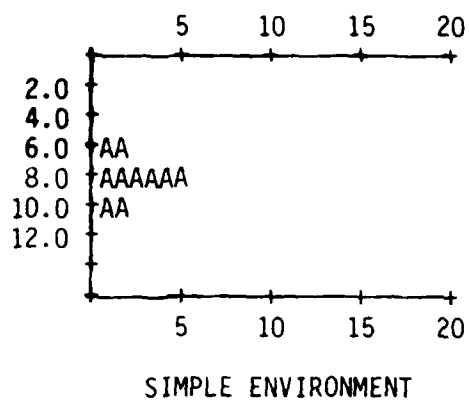


Figure 6.2 Histograms for BREADTH scores

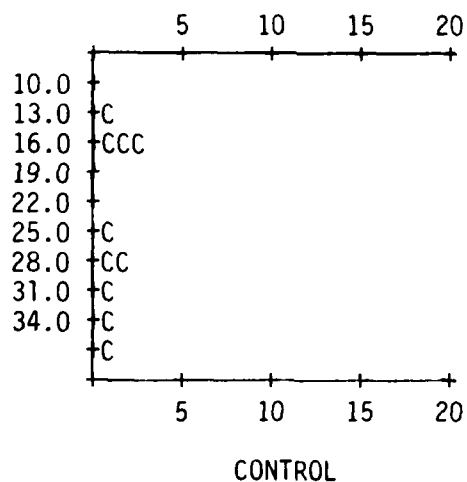
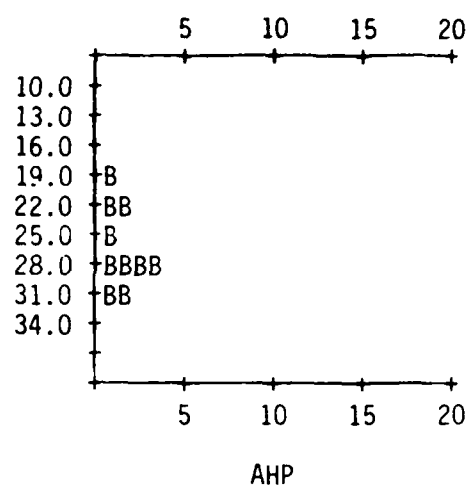
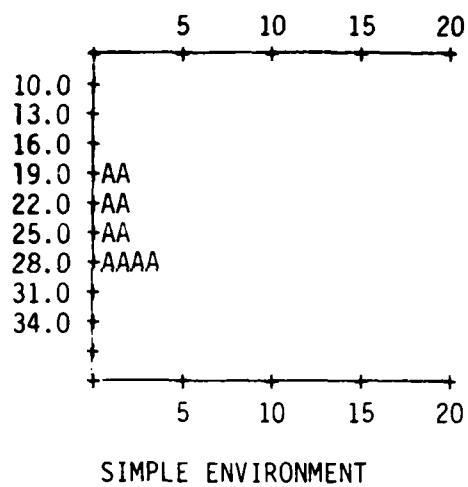


Figure 6.3 Histograms for NOVELTY scores

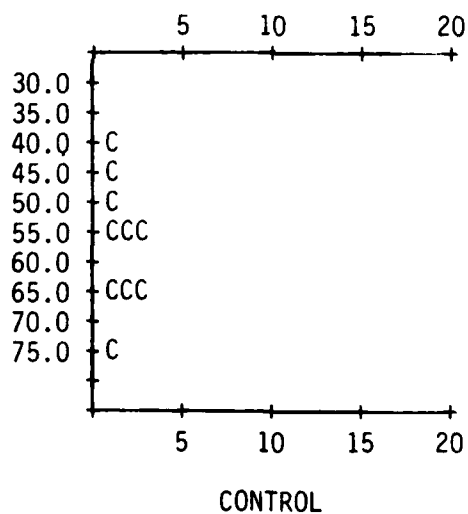
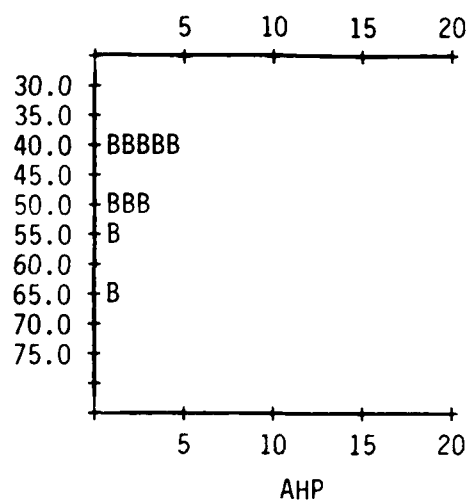
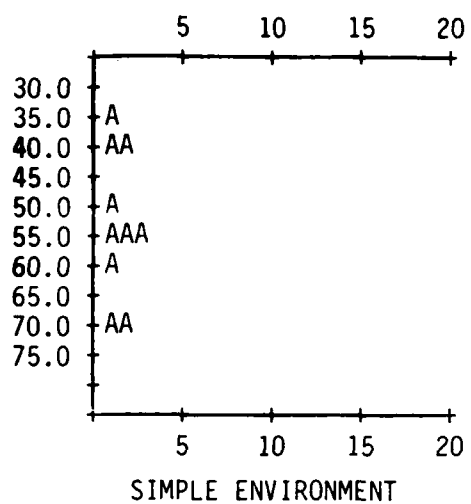


Figure 6.4 Histograms for FEASIBILITY scores

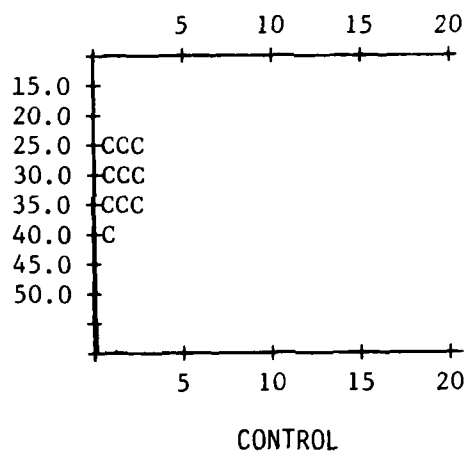
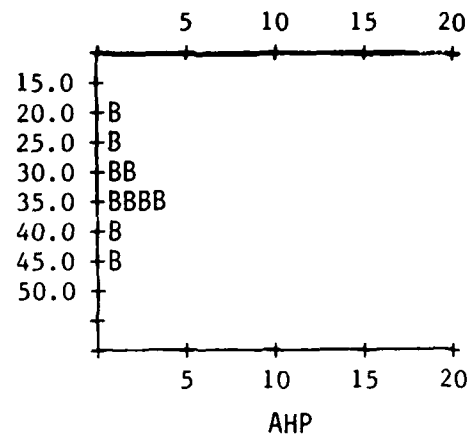
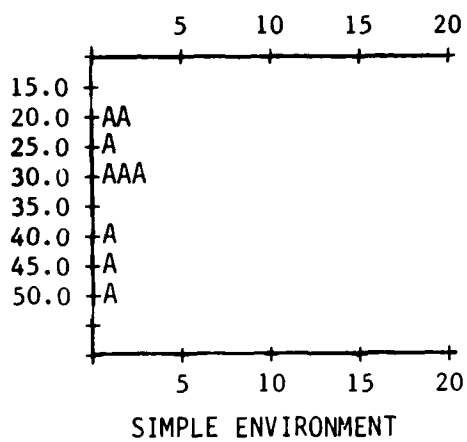


Figure 6.5 Histograms for BENEFIT scores

in Figure 6.3, the two treatment groups show a restricted range of novelty relative to the control group. In fact, the control group exhibits approximately twice the standard deviation of either the AHP group or the Simple Environment group, although there is no difference among the three groups in terms of average novelty score. The treatment groups may have eliminated extremely low average novelty scores, as well as extremely high average novelty scores. The feasibility histograms in Figure 6.4 show a skewed distribution for the AHP group. There actually was a trend toward less feasible options among the AHP subjects (mean=44.7) relative to the control subjects (mean=54.1). The AHP process seems to lead to a fairly automatic process of crossing dimensions and exploring the problem space. For example, one subject considered the actors in the problem (students, University, University Police, local community, local community police, etc.) and applied every option generated for one to all the actors. He first suggested that the University sponsor self-defense classes, a quite feasible option, but followed that suggestion with the less feasible options of requiring the University Police, the local community, and the local community police to sponsor self-defense classes. Such an approach may lead to infeasible suggestions which would be edited out as "nonoptions" by members of the control group. Finally, the benefit scores shown in Figure 6.5 also hint at some differences between the groups. The effect appears to be one of reducing the within group variability as we move from the Simple Environment to AHP to the Control group.

6.2.1. Interaction of Treatments and Cognitive Style

The interaction of field dependence and independence (as measured by the Embedded Figures Test) with the treatments was assessed by dividing the subjects in each condition into two groups, Field Dependent (above the median in total response time) and Field Independent (below the median in total response time). The data was then analyzed via a two-way (Field dependence by condition) analysis of variance for each of the 5 option measures: number, breadth, novelty, feasibility, and benefit. Field dependence did not interact with the effectiveness of the treatment groups for any of the measures (see Table 6.3). However, field dependence significantly affected the number of options generated ($F[1,24]=6.66, p<0.05$). The subjects who had low scores on the Embedded Figures Test, and thus were relatively field independent tended to generate more options than subjects with high scores on the Embedded Figures Test. However, the groups of low score subjects have approximately twice the variance of people with high scores. Although the analysis of variance is quite robust with respect to violations of homogeneity of variance, we must interpret this difference with caution. We did not perform a similar analysis of the interaction of attentional style with measures of option generation, because our subjects varied little on the subscores of the TAIS. Our population of undergraduate and graduate students may represent a narrow range of attentional styles.

6.3. Discussion

The two option generation aids tested in this experiment, the Analytic Hierarchy Process and the combination of information.

	SIMPLE ENVIRONMENT		AHP		CONTROL		F-STATISTICS	
	HIGH	LOW	HIGH	LOW	HIGH	LOW	INTERACTION df 2, 24	DEPENDENCE df 1, 24
NUMBER	14.8	19.2	13.6	24.4	12.6	17.1	.58	6.66 p < 0.05
BREADTH	7.6	7.8	8.2	9.2	5.6	6.8	.03	2.07
NOVELTY	22.9	23.3	24.0	25.8	22.7	24.9	.05	.34
FEASIBILITY	51.9	48.4	46.7	42.7	55.6	52.5	.00	.72
BENEFIT	28.9	29.9	29.8	31.3	28.1	28.3	.02	.10

Table 6.3 Statistics for Field Dependence

structuring, and creativity aids in the Simple Environment condition significantly increased the range or breadth of options subjects generated. However, the two treatment groups did not differ from the control group in the number of options, or average novelty, feasibility, or benefit of their options. Thus, there did not seem to be a trade-off of increasing breadth and decreasing number or quality of options generated.

Both the Analytic Hierarchy Process and the Simple Environment condition contain a variety of components which may have resulted in the subjects producing a broader range of options. Gettys and Fisher [23] proposed that the information used in generating a structure for a problem is retrieved from memory through a multistage search process. AHP is a procedure which requires the subject to formally represent the structure of the problem. The AHP program continues prompting subjects for more entries at each level of the hierarchy, and for more levels. Such prompting may increase the time subjects spend searching for aspects of the problem, and increase the number of elements in their problem representation. Therefore, they may later attempt to generate options in a broader range of categories. The structuring template in the Simple Environment condition would have a similar effect. The matrix presented was large; 5 categories (actors, goals, resources, constraints and environmental factors), by 7 possible examples of each category. Subjects attempted to completely fill in the matrix, which again may have prompted a broad view of the problem. Future research might center on pinpointing the source of the effect on breadth scores.

The AHP and Simple Environment treatments did not increase the number of options generated, nor their average novelty, feasibility, or benefit. The experiment should be regarded as a pilot study, because of the small numbers of subjects tested. However, new forms of the aids and new aids aimed specifically at fluency, novelty, feasibility, or benefit of options should be explored. The type of options generated may depend on the subjects interpretation of the experimenter's goals. For example, Hudson [38] studied creativity in schoolboys. He asked them to generate uses for common objects, first role-playing a serious engineer, second as a bohemian artist. The latter instructions resulted in far more novel responses than the former. Hudson suggests that everyone has the capacity to be creativity, if they believe the situation calls for creativity. We asked subjects to role-play being a member of a university advisory committee. Those instructions may have biased the subjects toward particular types of options. One aid might be to specifically ask subjects to play a variety of different roles.

The effectiveness of problem-solving aids may interact with the type of problem to which they are applied. Although no formal taxonomy of problems exists, we acknowledged the difference between open problems (broad problems for which there is no single right answer) and closed problems (problems with one clearly defined solution). Another distinction among problems may be drawn with regard to the type of solutions which are applicable. In the first experiment of this contract, subjects were asked to generate solutions to the problem of a downed aircraft. Subjects responded with lengthy plans to find and retrieve the craft. Each "option" actually consisted of a series of

steps in the plan. In the present experiment, options tended to be single steps. A single option might contribute partially to the solution of the problem, or it might solve the problem entirely. The options did not serially depend on one another, and in fact could be invoked simultaneously. Such differences in the type of solution (involved plans versus a collection of single options) required by a problem may determine which types of aids are best suited for a problem.

We measured "goodness" of option sets in a number of ways. Option fluency was scored simply by counting the number of options. Novelty, feasibility, and benefit were scored by the average subjective weightings of four judges. Breadth was determined by devising a set of categories of options on the basis of pretests. Although we feel these measures tap into several dimensions of intuitive notions of "good" solutions, they may be evaluated in other ways. For example, Davis [14] suggests measuring novelty on the basis of statistical frequency. An option which occurs just once in the total pool of options would receive a higher novelty score than an option which occurs two or more times. In the present experiment, we averaged the subjects' novelty, feasibility and benefit scores. An alternative would be to count the number of options which exceed a certain cutoff point on novelty, feasibility, or benefit, or to compute the proportion of options which exceed that cutoff point. When time is a factor, the rate of options generated, or the rate of novel options generated, may be computed. The choice of measures may be guided by an a priori conception of what will be relevant for applications of the problem solving aid. If people will use the problem-solving aid primarily under time pressure, rate measures

become more important during testing. Alternatively, if the aid will be used in an environment which weighs feasibility heavily, then that dimension should be stressed during testing.

Finally, the post-test questionnaires completed by the subjects in the Simple Environment and AHP groups give us some additional insights. As we would expect from our statistical results, there was significant variation within the treatment groups. Most subjects in the Simple Environment treatment attempted to use all the tools we provided. They often did this even when they felt the tools were of no particular benefit and despite our instructions to the contrary. Many found the word association tool to be superfluous and the brainstorming questions to be unhelpful. However, there were several strong positive responses to both the structuring template and the challenge assumptions protocol. A number commented that they would have benefitted from having a friend around to test their ideas against. We might interpret this as indicating the need for a simple option evaluation aid, something we did not provide.

Subjects in the AHP treatment most often commented on the program's lack of flexibility and robustness, reinforcing the lessons learned at Monterey. Several obviously found it hard to organize their thinking around the structure imposed by AHP, but others seemed to find it helpful and constructed elaborate hierarchies. Perhaps the most interesting reaction that we observed is that the majority of subjects used AHP as an option evaluation tool rather than a problem structuring tool. That is, they first generated options unaided and then used AHP to construct a value model against which to test the options. We had

expected that they would construct a prioritized hierarchy of decision factors and then use this to help them generate options.

Such variation in response to the treatments emphasizes the need to provide a selection of tools. Future experiments should include a wider choice of tools and should be designed so that frequency and length of tool use can be recorded. This data would be extremely valuable in helping build a picture of typical decision behaviors, and would help refine the content and form of the toolbox.

7. SUMMARY AND CONCLUSIONS

In this final chapter we summarize the research performed during the contract, discuss possible extensions of the ideas and provide insight into the likely impact of an operational Option Prompting Environment on Air Force decision making.

7.1. Project Status

The purpose of the effort described in this report was to define and explore techniques for helping decision makers generate options in decision problems. In performing this research we completed a variety of tasks:

- (1) We prepared an extensive bibliography of appropriate literature together with a commentary on the key publications.
- (2) We developed a computer implementation of the Analytic Hierarchy Process.
- (3) We performed an experiment designed to test the effectiveness of AHP as an option generation aid.
- (4) We devised the concept of an Option Prompting Environment as a fundamental component in the solution of the option generation problem.
- (5) We performed a second experiment designed to test a simple "paper" version of the environment, at the same time re-testing the AHP aid.

Our main results and conclusions fall into two broad categories: those that are conceptual, and those that are methodological. Thus part of our effort has been to define the problem of option generation and what it means to aid the decision maker in this task, and part has been to define and use procedures for experimentally evaluating our ideas.

The conceptual issues may be summarized as:

- (1) The task of option generation is not one that exists in isolation. Instead, it is at the core of decision making, which is an iterative and dynamic process. We should not, therefore, treat option generation independently, but have to concern ourselves with the overall problem of decision making.
- (2) Option generation itself is a creative activity that cannot be automated for the "open" problems in which we are interested. What is required are methods for enhancing the ability of the decision maker to "break set" and thereby overcome his inherent conceptual blocks.
- (3) There are a variety of reasons why options do not get generated. These are related to the various stages of the decision process and the corresponding cognitive limitations of human decision makers. In general it is not sufficient to provide only a single options prompting aid. Rather the decision maker needs an appropriate environment containing several aids that can be selected and used according to the specific decision phases in which the decision maker wants or needs support.

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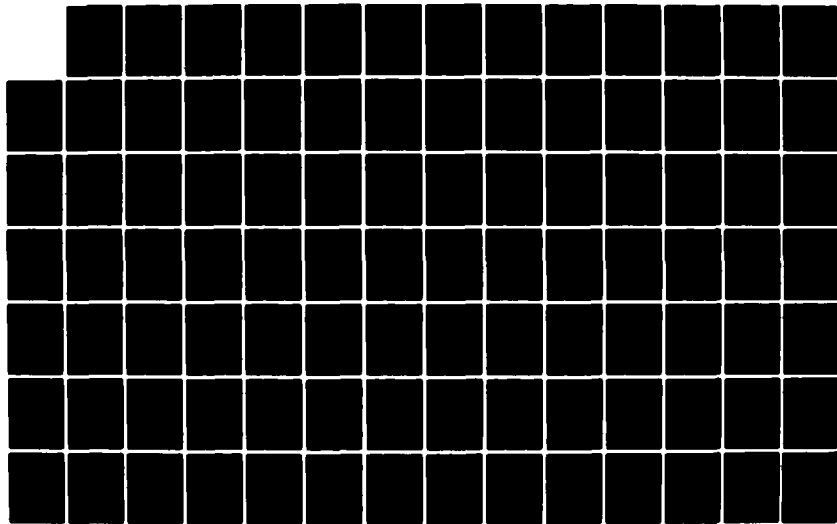
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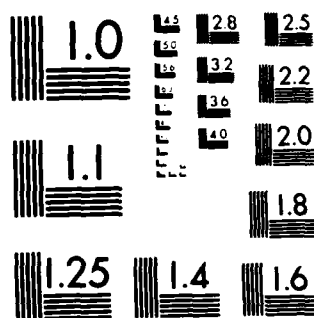
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- (4) The environment itself can be simple or complex. At its simplest, it merely provides a set of tools and rules for their use (a toolbox), and procedures for recording options. As it becomes more complex, it incorporates explicit knowledge about the decision making process and the limitations of human decision makers. It could serve either as an operational aid or as a training environment.
- (5) What constitutes an option depends, at least in part, on the type of problem. For the Downed B-52 scenario in the Monterey experiment, an option has the character of a plan, with the set of options consisting of alternative plans. In the campus security problem, however, an option is a single step that might be taken, either alone or in conjunction with others in the option set.
- (6) Performing the AHP provides a useful structure, indicates the breadth of decision factors to consider and the priorities of these factors.

Our comments on the methodological issues may be summarized as:

- (1) There is a severe measurement problem, both in defining appropriate measures of effectiveness and in making them operational. In our experiments we asked subjects to generate as many creative options as possible, leaving aside the question of whether this is always the most appropriate approach. We are concerned with aspects of the set of options as well as with the individual options themselves. That is, we are interested in the number and breadth of options generated not just the goodness of the individual options. The development of consistent valid measuring instruments for

subjective concepts such as novelty, feasibility and benefit is non-trivial.

- (2) Computerized aids present a special set of difficulties when used experimentally. There are difficult questions that remain to be answered about the proper design of the man-machine interface and the general acceptability of such tools. Not only may the user be unfamiliar with the content of the aid, but he may also be unfamiliar with the general concept (and limitations) of computer-based aids. Experimental evaluation of the concept of an aid (eg. AHP) cannot be separated from its embodiment in the computer and the procedures to use it. It is essential, therefore, to provide adequate training.
- (3) Performing formal experiments with decision aids is complicated by the complexity of human decision making behavior. In order that the aid receives a realistic test, we need to provide real-world problems. This makes it hard to control the independent variables in the experiment and so conduct a rigorous test of the experimental hypothesis. This is a major methodological issue that is not resolved.

Finally, our pilot experiments provide support for our contention that both the AHP and an option prompting environment can aid the decision maker in generating options. However, the effects observed are small. The Monterey experiment provided us with some qualitative understanding of the issues and in the Stanford experiment we were able to test these issues more formally.

7.2. Future Research

This has been a basic research effort to determine the nature of the option generation problem. In exploring the many issues that have arisen we have been able to define a series of questions that should be considered in any future research. In particular we believe that an implementation of the Option Prompting Environment would be an appropriate next step. The crucial elements of this are the knowledge base and the toolbox of aids. Without the knowledge base, the toolbox is just a passive collection of aids unable to help the decision maker when he does not know how to proceed; without the toolbox, the knowledge base can have no operational expression.

However, building of the environment should be accompanied by a careful experimental learning and testing program. It is important to evaluate concepts and tools as they are added to the environment, with both formal experiments and the collection of verbal protocols capable of providing valuable data.

In order to achieve these goals, seven subtasks need to be performed.

- (1) Perform research on theories of the decision making process. These should have sufficient power that they can account for a variety of observed decision making behaviors and will allow the construction of the knowledge base. Embedded in the knowledge base will be information about cognitive limitations, personal decision styles and tool preferences, as well as normative procedures for decision making.

- (2) Choose a specific class of decision makers and define experimental decision situations germane to that class.
- (3) Define and build problem structuring aids. Particular attention should be paid to the integrated use of multiple types and sources of information, and to the representation of this information in human readable forms. These aids need to build upon existing work in the areas of decision templates, decision trees, and influence diagrams.
- (4) Enhance the implementation of AHP paying particular attention to the man-machine interface questions.
- (5) Define and build a variety of aids for stimulating option generation creativity. These aids should be designed to facilitate the capturing of ideas as they occur, rather than in rigidly predefined orders and formats. Emphasis should be placed on, but not limited to, deriving acceptable computerized versions of tools used in Brainstorming, Synectics, Conceptual Blockbusting and Lateral Thinking.
- (6) Define and build option evaluation aids. These need to be at a variety of levels of detail, from subjective evaluation protocols to detailed models. The aids need to build on existing work in the general areas of value elicitation, and the specific models available in the domain of the specific class of decision makers selected.
- (7) Research and define consistent valid measures of option generation performance in complex decision situations.

7.3. Impact on Air Force Decision Making

On the basis of the insights gained performing the research tasks enumerated in Section 7.1 above, we believe the development and use of operational Option Prompting Environments containing robust knowledge bases, diverse selections of tools, and intelligent man-machine interfaces would impact decision making situations in the Air Force along many dimensions. The classes of decision makers affected could range from complex equipment or system operators to generals and staffs making command decisions. The types of decision situations impacted could range from simple "closed" decision situations (e.g., recognizing the state of a system in a training environment and implementing a single "school" action prescribed for that state) to complex "open" decision situations in an operational environment wherein there are no satisficing options evident at first. The decision making process in each specific decision situation may have more attention focussed on it. Undesirable cognitive biases could be procedurally mitigated. A wide variety of cognitive styles could be accommodated. The decision processes could more easily be studied, resulting in decision theory extensions and methodology improvements.

Our basic research was kept at a generic level for the most part. However most of the specific military decision situations posed during the study involved command decisions at the General level. Such decision situations may often be characterized by a large number of important decision factors, some of which can only be qualitatively assessed, while several others have uncertainty associated. The decision process is often conducted by the General and his staff, some of whom are

"nuggets" in the command level decision processes. We believe that an Option Prompting Environment supporting the General and his staff would be valuable to both the experienced member and the neophyte in the organization. The experienced decision maker would be aided in quickly gaining data, structuring his decision problem, and in allocating appropriate time, effort and staff to considering the various decision factors and phases of the decision process. He would also benefit from mechanisms to avoid the effects of, or at least be aware of, cognitive biases such as the anchoring, availability, and selective perception biases. The Option Prompting Environment should encourage the decision maker to be creative with respect to the many aspects of difficult decision situations. It should help him check for the completeness of his approach and thereby provide a sense of confidence and motivation. The inexperienced staff could benefit from templates and knowledge based guidance which the Option Prompting Environment would provide. It would also provide a vehicle for communication and on-the-job training.

In formal training the Option Prompting Environment should be beneficial in prompting the decision maker trainee, when he is stuck, to select and begin a next appropriate action, instructing him on the use of any associated tool. It could also point out when the trainee is likely to suffer the effects of the various types of biases. For example, an evaluation tool may be an available low fidelity model of an important part of the decision situation. The decision maker is likely to use the specific quantitative output of this model in his other considerations and that output may produce an anchoring bias when considering even larger variations on the decision situation modelled.

In lower level decisions, such as complex equipment or system control decisions, the operator (i.e., the decision maker) upon recognizing the state of his system in the environment, may select an option specified in his training. Hence the operational decision making is rather straightforward. However, as conditions and/or equipment are modified, the researchers/developers/tacticians/trainers that prescribed the specified option should occasionally reconsider the option prescribed. At that time the Option Prompting Environment could be important, since the possibly new option to be prescribed may subsequently be used repeatedly by a large number of decision makers.

The Air Force is willing to invest relatively large amounts of money, time and effort in the explicit training of pilots, other operator personnel, and technicians; but little for explicit training of Generals and staff officers in one of their most important activities: command decision making. Providing decision support systems such as Option Prompting Environments would provide mechanisms for both staff colleges and operational staffs to focus efforts in this area. In particular, it may encourage them to focus on making "better" decisions (i.e., generating and selecting a "good" alternative) instead of immediately developing a plan for an "OK" alternative.

Command decision making style is clearly dependent on the specific decision makers involved. If a decision maker decides to use a system, such as an Options Prompting Environment, then he must submit to the constraints inherent in the system, thereby changing his style. If this change is substantial it may affect his capability to operate creatively or efficiently. If he is willing to use a system, then he should be

able to perform at least as well and as confidently as without the system. Of course the amount of training he has experienced may significantly impact his effectiveness with the system. Flexibility within the system, such as a selection of different tools and a user friendly interface, may circumvent any overall stifling effects while providing specific useful information.

The final significant anticipated impact stated here relates to more research and development in decision making, to which the generation process can be so critical. With current aircraft, sensor, communication, navigation, and logistic support systems, command and control has become the most critical element of many Air Force unit operations; and perhaps decision making is the most important sub-element. A physical and software system, such as an Options Prompting Environment, will be identified explicitly with this critical warfare functional element. Such an identifiable entity should focus attention and foster efforts to achieve both deeper understanding of and better procedures for operational Air Force decision makers.

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The literature that is potentially relevant to Options Generation is vast, and it is clearly infeasible to gather it all together in a single bibliography. Our goal has thus been to construct a set of references that reflect the major relevant disciplines involved. We have included those publications which have had most influence on our thinking, several other key papers and a variety of secondary studies. Also included are some review papers and texts, each of which contains its own extensive bibliography. In this way, we provide a comprehensive introduction to the literature.

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- [24] C.F.Gettys, C.Manning, T.Mehle, S.D.Fisher.
Hypothesis Generation: Final Report of Three Years of Research.
Technical Report TR15-10-80, Decision Processes Lab.,
Univ. Oklahoma, 1980.
A companion to [24] and equally important reading.
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An Evaluation of Human Act Generation Performance.
Technical Report TR15-8-81, Decision Processes Lab.,
Univ. Oklahoma, 1981.
A companion to [23] and [24]. A key paper.

- [26] W.J.J.Gordon.
Synectics.
Harper and Row, New York, 1961.
A book for the layman that describes the motivation for the Synectics concept; many examples of its successful application.
- [27] R.M.Gulick.
Documentation of Decision-Aiding Software: Introductory Guide.
Technical Report 79-1-93, Decisions & Designs Inc., 1980.
The basic documentation for the decision analysis software developed by Decisions and Designs Inc.
- [28] B.Hayes-Roth, F.Hayes-Roth.
A Cognitive Model of Planning.
Cognitive Science 3:275-310, 1979.
A cognitive science view of the problem of planning. It describes a model of planning and its implementation as a computer simulation. Valuable for its discussion of some basic questions, but of secondary importance to Options Generation.
- [29] R.G.Head, F.W.Short, R.C.McFarlane.
Crisis Resolution: Presidential Decision Making in the 'Mayaguez' and Korean Confrontations.
Westview Press, Boulder, CO, 1978.
A most insightful discussion of crisis decision making with a particularly detailed analysis of two international incidents. Good background reading.
- [30] M.Henrion.
Designing a Computer Aid for Decision Analysis.
In Proc. Int. Conf. on Cybernetics and Society.
IEEE, October, 1979.
A description of a prototype decision aid that has some interesting interactive features. A good example of the work being done in this area.
- [31] R.M.Hogarth.
Judgement and Choice.
Wiley, New York, 1980.
A key reference. An exceptionally good book that takes a psychological view of decision making. It contains excellent descriptions of biases and heuristics, and discusses many of the issues we have raised in this report.
- [32] R.M.Hogarth, S.Makridakis.
Forecasting and Planning: An Evaluation.
Management Science 27(2):115-138, 1981.
A good review article that shows how biases and heuristics impact the problems of forecasting and planning in a business organization. Contains some material from [31].

- [33] R.M.Hogarth.
Beyond Discrete Biases: Functional and Dsyfunctional Aspects of
Judgemental Heuristics.
Psychological Bulletin 90(2):197-217, 1981.
A good example of research into the nature of biases and
heuristics. It contains an interesting discussion of the origins
and functional nature of the behavioral anomalies.
- [34] C.A.Holloway.
Decision Making Under Uncertainty.
Prentice-Hall, 1979.
A basic text on decision analysis, containing basic introductory
material and many examples.
- [35] C.W.Holsapple, H.Moskowitz.
A Conceptual Framework for Studying Complex Decision Processes.
Policy Sciences 12:83-104, 1980.
A marginally relevant discussion of some theoretical questions in
the analysis of complex problems.
- [36] G.P.Huber.
Cognitive Style as a Basis for Designing MIS and DSS: Much Ado
About Nothing.
Working Paper 11-81-29, Graduate School of Business,
Univ. Wisconsin-Madison, 1981.
A key paper on cognitive style. It contains a carefully reasoned
argument against the need to take account of cognitive style in the
design of decision support systems. An updated version of this
paper will appear in Management Science.
- [37] G.P.Huber.
Organizational Information Systems: Determinants of their
Performance and Behavior.
Management Science 28(2):138-155, 1982.
An interesting discussion of the causes for the failure of many
management information systems. It proposes a series of models that
can account for observed behavior. Only marginally relevant to the
Options Generation problem.
- [38] L.Hudson
Frames of Mind: Ability, Perception and Self-Perception
in the Arts and Sciences.
Metheun, London, 1968.
A useful background text on creativity and how it can affected by
the nature and context of the task environment.

- [39] P.Humphreys, W.McFadden.
Experience with MAUD: Aiding Decision Structuring Versus
Bootstrapping the Decision Maker.
Acta Psychologica 45:51-69, 1980.

A detailed description of a decision aid for multi-attribute decision making. It also attempts to define a methodology for performance assessment.

- [40] I.L.Janis, L.Mann.
Decision Making.
The Free Press, New York, 1977.

A valuable text that develops a model of decision making under stress. This work has influenced many authors because it attempts a prescription for improving decision making under such circumstances.

- [41] R.H.Johnson.
Individual Styles of Decision Making.
Personnel and Guidance Journal :530-536, May, 1978.

A good discussion of the concept of decision style, which develops two-dimensional model of the components of style.

- [42] S.C.Johnston, A.Freedy.
Group Decision Aiding: A New Dimension in Management Decisions.
In Proc. Int. Conf. Cybernetics & Society. IEEE., Boston, 1980.

A brief description of a commercially available group decision aid. Interesting mainly for it claim that the interactive nature of the aid improves options generation performance. However, this appears to be merely anecdotal, no experimental evidence is offered.

- [43] M.J.Jusko, R.G.Whitfield.
A Guide to IDAP, Version 2: An Interactive Decision
Analysis Procedure.
Technical Memo ANL/EES-TM-126, Argonne National Lab., 1980.

The basic documentation for a large complex decision analysis package developed at the Argonne National Laboratory.

- [44] D.Kahneman, A.Tversky.
Intuitive Prediction: Biases and Corrective Procedures.
In S.Makridakis, S.C.Wheelwright (editors), Forecasting. North-
Holland, 1979.

A key discussion of the prediction bias and ways in which it might be overcome. This paper is especially valuable because it shows that decision makers can be helped to overcome the biases that they exhibit.

- [45] D.Kahneman, P.Slovic, A.Tversky (editors).
Judgement Under Uncertainty: Heuristics and Biases.
Cambridge U.P., New York, 1982.

A key reference. An extremely useful collection of papers that cover the whole range of biases and heuristics. A basic text.

- [46] C.W.Kelly, R.M.Gulick, R.R.Stewart.
The Decision Template Concept.
Final Technical Report PR80-17-99, Decisions & Designs Inc., 1980.
A description of a template approach to decision aiding. This report describes attempts by Decisions and Designs Inc. to build operational decision aids for various military organizations. It contains some interesting case studies.
- [47] A.Koestler.
The Act of Creation.
Macmillan, New York, 1964.
An extensive investigation into the nature of human creativity. A most valuable background text.
- [48] H.A.Linstone, M.Turoff.
The Delphi Method: Techniques and Applications.
Addison-Wesley, 1975.
A book which discusses the theory and practice of the Delphi group decision making procedure.
- [49] H.C.Lucas.
An Experimental Investigation of the Use of Computer-Based Graphics in Decision Making.
Management Science 27(7):757-768, 1981.
A discussion of some experiments to investigate the value of computer graphics in a decision support system. An attempt to correlate performance with measures of cognitive style appears inconclusive.
- [50] A.S.Luchins
Mechanization in Problem Solving.
Psychological Monographs 54(248), 1942.
A classic psychology text on problem solving.
- [51] K.R.MacCrimmon, R.N.Taylor.
Decision Making and Problem Solving.
In M.D.Dunette (editor), Handbook of Industrial and Organizational Psychology. Rand-McNally, 1975.
A paper which attempts to characterize decision style in terms of four psychological attributes. It contains a report of some experimental work.
- [52] T.Mehle.
Hypothesis Generation in an Automobile Malfunction Inference Task.
Technical Report TR25-2-80, Univ. Oklahoma,
Dept. Psychology, 1980.
A report by a member of the Gettys group that explores human performance in a particular options generation task. A primary reference.

- [53] M.W.Merkhoffer, B.E.Robinson, R.J.Korsan.
A Computer Aided Decision Structuring Device.
Final Report 7320, SRI International, 1979.

An introduction to the decision aiding software developed by SRI International.

- [54] B.W.Morton.
A Computer-Based Decision Analysis Support System.
Master's thesis, AF Inst. Technology, School of Engineering, 1979.

A dissertation that describes a prototype decision aid that extends some software originally developed by Decisions and Designs Inc.

- [55] I.B.Myers, K.C.Briggs.
Myers-Briggs Type Indicator.
Consulting Psychologists Press, Palo Alto, CA., 1977.

A discussion, and justification, of a widely used test for cognitive style.

- [56] R.M.Nideffer.
Test of Attentional and Interpersonal Style.
J. Personality and Social Psychology 34(3):394-404, 1976.

A description, and justification, for the TAIS test used in our Stanford experiment.

- [57] A.Osborne
Applied Imagination (3rd ed.)
Scribner's, New York, 1963.

The book that introduces the Brainstorming technique. It gives the motivation for the procedure and contains many examples of its successful application.

- [58] J.R.Payne, et al.
A Brief Survey of Potential Decision Aids for the Task Force Commander and his Staff.
Research Memo NWRC-RM-84, SRI, 1975.

A research report that gives an overview of potential decision aids for a particular user in the Navy.

- [59] J.R.Pearl, A.Leal, J.Saleh.
GODDESS: A Goal Directed Decision Structuring System.
IEEE Trans. Pattern Analysis and Machine Intelligence
PAMI-4(3):250-262, 1982.

A most interesting paper that describes an unusual approach to the problem of providing computerized support for decision structuring. This is a key paper, perhaps most important for its recognition that goals are the primary element in generating decision alternatives.

- [60] G.F.Pitz, N.J.Sachs, J.Heerboth.
Procedures for Eliciting Choices in the Analysis of Individual Decisions.
Organizational Behavior and Human Performance 26:396-408, 1980.
A key paper in options generation. A report on experiments designed to assess the determinants of choice generation in a restricted set of personal decisions.
- [61] G.F.Pitz, N.J.Sachs, M.T.Brown.
Eliciting a Formal Problem Structure for Individual Decision Analysis.
Technical Report TRAEP, vol 2, no 2, Southern Illinois Univ. Carbondale, Dept. Psychology, 1980.
A companion paper to [60] containing the results of some additional experiments.
- [62] D.J.Power.
Case Study of the Design and Development of a Decision Support System: DECAID.
Working Paper MS/S 82-02-1, College of Business and Management, Univ. Maryland, 1982.
A careful discussion of the development of a flexible decision aiding package developed for a personal computer. Most interesting for its recognition that successful decision aiding is accomplished by providing a variety of tools.
- [63] G.M.Prince.
The Practice of Creativity.
Collier Books, New York, 1970.
Another book which describes the Synectics approach to creative thinking.
- [64] H.Raiffa.
Decision Analysis: Choice under Uncertainty.
Addison-Wesley, 1974.
A standard decision analysis text. It contains the basic theory and many examples.
- [65] D.W.Rajala, A.P.Sage.
On Measures for Decision Model Structuring.
Int. J. Systems Science 11(1):17-31, 1980.
A paper which gives an example of the use of sensitivity analysis to guide the development of a decision tree. It contains a discussion of measures of modelling and measures of information.
- [66] B.E.Robinson
Crisis Decision Analysis.
PhD Thesis, Stanford University, 1979.
A dissertation that contains a proposal for a decision aid to be used in crisis decision making. Most notable for its concept of a template for preliminary structuring of the decision problem.

- [67] T.L.Saaty.
The Analytic Hierarchy Process.
McGraw-Hill, New York, 1980.

A key reference. This book contains a basic introduction and justification for the Analytic Hierarchy Process.

- [68] T.L.Saaty, L.G.Vargas.
The Logic of Priorities.
Kluwer Nijhoff, Boston, 1981.

A companion to [67] containing many real world applications of AHP.

- [69] C.R.Schwenk, R.A.Cosier.
Effects of the Expert, Devil's Advocate, and Dielectical Inquiry
Methods on Prediction Performance.
Organizational Behavior and Human Performance 26(409-424), 1980.

A discussion of a variety of group decision making procedures. Most interesting for its conclusion that a non-combative devil's advocate approach is most effective.

- [70] H.A.Simon.
Administrative Behavior.
The Free Press, New York, 1976.

A classic discussion of organizations and their behavior, but only marginally relevant at this stage of our research.

- [71] P.Slovic, B.Fischhoff, S.Lichtenstein.
Behavioral Decision Theory.
Annual Review of Psychology 28:1-39, 1977.

A key paper. This is a detailed review of behavioral decision theory.

- [72] R.Steeb, S.C.Johnston.
A Computer-Based Interactive System for Group Decision Making.
IEEE Trans. Systems, Man, and Cybernetics SMC-11(8):544-551, 1981.

A companion to [42] containing some additional discussion of the effectiveness of this particular group decision aid.

- [73] M.I.Stein.
Stimulating Creativity: Vol. 1.
Academic Press, New York, 1974.

One of two classic volumes on creativity and procedures for improving it.

- [74] R.N.Taylor, M.D.Dunnette.
Relative Contribution of Decision Maker Attributes to
Decision Processes.
Organizational Behavior and Human Performance 12:286-298, 1974.

A paper that attempts a taxonomy of attributes which determine decision making style. Most useful for its approach and discussion of the basic problems in this area.

- [75] R.M.Tong
A Preliminary Experimental Investigation of an Options Prompting Aid.
 Advanced Information & Decision Systems,
 Technical Note TN3012-4, November 1981.
 A complete report of our Monterey experiment.
- [76] A.Tversky, D.Kahneman.
 Judgement Under Uncertainty.
Science 185:1124-1131, 1974.
 A good description of the problems of making decisions under uncertainty. The style of the paper is such that this would be a useful first introduction to the issues.
- [77] A.Tversky, D.Kahneman.
 The Framing of Decisions and the Psychology of Choice.
Science 211:293-311, 1981.
 A key paper. A clear discussion of the framing problem, together with some very stimulating experimental evidence.
- [78] T.S.Wallsten (editor).
Cognitive Processes in Choice and Decision Behavior.
 Lawrence Erlbaum, Hillsdale, NJ., 1980.
 A good collection of papers that cover a large number of issues in behavioral decision theory. Excellent background material.
- [79] S.R.Watson, R.V.Brown.
 The Valuation of Decision Analysis.
J. Royal Stat. Soc., Ser. A 141(1):69-78, 1978.
 A decision analysis paper that attempts to formalize a procedure for assessing the value of actually performing a decision analysis; marginally relevant.
- [80] W.A.Wicklegren.
Cognitive Psychology.
 Prentice-Hall, Englewood Cliffs, NJ., 1979.
 A standard text on the psychology of problem solving. It contains, among other things, a discussion of general problem solving strategies.
- [81] R.Willensky.
A Model for Planning in Complex Situations.
 Memorandum UCB/ERL M81/49, Univ. California, Berkeley, Electronics Research Lab., 1981.
 An artificial intelligence approach to the planning problem. This report contains some speculations into the nature of the planning process and offers a high level model that is to be implemented in an experimental computer program. Only marginally relevant at this stage of our research.

- [82] J.A.Wise.
Cognitive Basis for an Expanded Decision Theory.
In Proc. Int. Conf. on Cybernetics & Society. IEEE, 1979.
A discussion of a model of human decision making that emphasises a gestalt psychology approach. It argues that if a problem is well structured then it is obvious what the appropriate course of action should be.
- [83] H.A.Witkin
Individual Differences in Ease of Perception of Embedded Figures.
J. Personality 19:1-15, 1950.
A classic paper that provides some of the justification for the Embedded Figures Test of [84].
- [84] H.A.Witkin, P.K.Oltman, E.Raskin, S.A.Karp
Embedded Figures Test.
Consulting Psychologists Press, Palo Alto, CA., 1971.
The basic introduction to the Embedded Figures Test used in our Stanford Experiment.
- [85] J.G.Wohl.
Force Mangement Decision Requirements for Air Force Tactical Command and Control.
IEEE Trans. Systems, Man, and Cybernetics
SMC-11(19):618-639, 1981.
A key paper. An excellent discussion of the need for decision aids in Air Force Tactical Command and Control. It contains several good characterizations of the issues and a descriptive model of the decision making process that helps focus on the key problems.
- [86] R.M.Yerkes, J.D.Dodson
The Relation of Strength of Stimulus to Rapidity of Habit Formation
J. Comparative Neurology of Psychology 18:459-482, 1908.
A classic psychology paper that introduces the idea that performance is a curvilinear function of arousal.
- [87] R.W.Zmud.
Individual Differences and MIS Success: A Review of Empirical Literature.
Management Science 25:966-979, 1979.
A valuable review of the experimental evidence both for and against the importance of individual decision style in determining the value of various management information systems; good background reading.

APPENDIX A: SUMMARIZED BIBLIOGRAPHY

In this appendix we summarize the comments contained in the annotated bibliography by constructing a pair of cross-referenced tables to the bibliography entries. Our scheme for categorizing the literature is given in Table A1 where we show three major categories and several sub-categories. Section 2.1 of the main report gives a detailed definition of our terms and a discussion of our reasons for choosing them. Table A2 summarizes each entry by placing it in appropriate categories from Table A1; for example, entry #1 is a review of creativity and problem solving in a management science context, whereas entry #2 is a collection of techniques for improving individual creative thinking and problem solving ability. Table A3 lists entries by topic and importance and can be used to access the literature if a subject is known. So, entry #18 is a primary reference for cognitive biases and styles, and entry #1 is a secondary reference for creativity. Notice that the topics are not identical to those used in Table A2. This allows us to provide a more flexible breakdown of the literature. In both these tables, bibliography entries may appear in more than one category, reflecting the wide ranging nature of some studies.

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Table A1. Literature Categories

<u>DISCIPLINE</u>	<u>SUBJECT</u>	<u>TYPE</u>
1. "Internal"	1. Behavioral decision theory	1. Experimental
- psychology	2. Creativity	2. System building
- cognitive science	3. DSS/MIS	3. Theoretical
- artificial intelligence	4. Methodology	4. Miscellaneous
2. "External"	5. Problem solving	- review
- decision analysis	- planning	- tutorial
- management science	- decision analysis	
- systems engineering	- logic/reasoning	
	- organization theory	

Table A2. Literature by Category

Entry No.	Discipline		Subject					Type			
	1	2	1	2	3	4	5	1	2	3	4
1		*		*			*				*
2	*			*			*				*
3	*			*				*		*	
4	*			*				*		*	
5	*			*				*		*	
6		*			*					*	
7	*		*	*				*	*		
8		*					*			*	
9		*		*				*			
10		*		*							*
11	*			*			*			*	*
12	*						*	*		*	
13		*			*					*	
14	*						*			*	*
15		*					*	*			
16											*
17	*		*						*	*	*
18	*		*					*			
19	*		*						*	*	*
20	*						*		*		
21		*					*	*	*		
22	*			*					*	*	*
23	*		*			*	*	*	*		
24	*		*				*				*
25	*		*			*	*	*	*		
26		*		*			*		*		*
27		*			*			*			
28	*						*		*		
29		*					*				*
30		*			*			*			

Table A2. (Continued)

Entry No.	Discipline		Subject					Type			
	1	2	1	2	3	4	5	1	2	3	4
31	*		*							*	*
32	*		*				*			*	*
33	*		*					*			
34		*					*			*	*
35		*					*			*	
36	*		*		*					*	
37	*		*		*					*	
38	*						*			*	*
39		*			*			*	*		
40	*		*								*
41	*		*							*	
42		*			*				*		
43		*			*				*		
44	*		*					*			
45	*		*								*
46		*			*				*		
47	*			*						*	*
48		*					*		*		
49		*			*			*	*		
50	*						*				*
51	*						*			*	
52	*		*					*			
53		*			*				*		
54		*			*				*		
55	*					*					*
56	*					*					*
57		*		*							*
58		*			*						*
59		*			*				*	*	
60	*		*			*	*	*		*	

Table A2. (Continued)

Entry No.	Discipline		Subject					Type			
	1	2	1	2	3	4	5	1	2	3	4
61	*		*			*	*	*		*	
62		*			*				*		
63		*		*							*
64		*					*			*	*
65		*				*	*			*	*
66		*		*					*	*	
67		*					*			*	
68		*					*			*	
69	*		*					*			
70		*					*			*	*
71	*		*								*
72		*			*				*		
73	*			*							*
74	*		*							*	
75		*		*				*			
76	*		*					*		*	
77	*		*					*		*	
78	*		*								*
79		*					*			*	
80	*		*							*	*
81		*					*			*	
82	*		*							*	
83	*		*			*		*		*	
84	*					*				*	
85		*		*		*			*	*	
86	*		*					*		*	
87		*		*						*	*

Table A3 Literature by Topics

TOPIC	PRIMARY REFERENCES	SECONDARY REFERENCES
Cognitive biases	19, 32, 33, 44, 45, 71, 76, 77	18
Cognitive style	19, 32, 36, 41, 45, 71, 87	12, 74
Decision aids	27, 39, 42, 43, 46, 53, 58, 59, 85	13, 30, 49, 54, 62, 66, 72
Group decision making	15, 26, 42, 48, 57	32, 40, 69, 70, 72
Theories of decision making	8, 19, 29, 31, 37, 40, 64, 67	17, 20, 21, 28, 34, 35, 51, 65, 68, 70, 79, 81, 85
Creativity	2, 4, 5, 14, 26, 47, 57	1, 3, 9, 10, 22, 38, 50, 63, 73, 82
Options generation	6, 23, 24, 25, 52, 60, 61	7, 75

APPENDIX B: A MATHEMATICAL DESCRIPTION OF OPTION GENERATION

In this appendix we present a mathematical model of option generation. Its purpose is mainly illustrative, and we make no claims for its psychological validity. Its value, however, is that it enables us to improve our understanding of the areas in which an option prompting environment could provide support.

We start by considering the problem recognition phase of decision making and develop a model that captures the concept of "unsatisfactory plausible outcomes". This model naturally leads us to a second one that describes the dynamic nature of the options generation process in terms of an heuristic search algorithm. In both models, we see how the formulation can be used to define appropriate decision aids.

Problem Recognition

In any situation, the first question that a decision maker faces is "Do I have a decision to make?" If he is being instructed to deal with a specific problem in a specific way then the answer to this is trivial. However, in many situations the answer is not. We believe that in many cases the ability to generate good options hinges on early detection of the decision problem.

We need to distinguish between two kinds of activity. In the first, or "tactical", activity simple adjustments are made to a nominal course of action in order to adapt to a real-time situation. In the other, or "strategic", activity a more involved thinking process is carried out to determine a new course of action. We shall refer to the former activity

as an operational procedure and the latter as option generation. Usually an operational procedure requires only local and micro information about the deviation of the actual activity from the nominal course of action. Options Generation, on the other hand, requires global but macro information about the overall situation.

Let us consider a decision maker at a specific level in the decision hierarchy. We assume that a certain nominal course of action is being taken and that the operational procedures are carried out in real-time. The question now is, when will the decision maker think that the nominal course of action is inappropriate and that a new course of action needs to be determined. To answer this, we shall extend Simon's satisficing model and relate it to the option generation process. We argue that due to bounded rationality, the decision maker tends to continue with an established operational procedure so long as he is satisfied with the plausible outcomes resulting from that procedure. So, the issues are: what are plausible outcomes, and when is the decision maker dissatisfied with them.

Let us first discuss the notion of a plausible outcome. Assume that a nominal course of action is to be taken. However, due to the fact that the future event is uncertain, or is being manipulated by the other players in the environment, an operational procedure has the character of a simple feedback mechanism. As a result, the decision maker derives a set of plausible outcomes. To represent this symbolically, let us denote the future event by w , and the adjustment feedback mechanism by $u(.)$. Then the outcome caused by w and $u(w)$ is denoted by $y(u(w), w)$. If the decision maker anticipates that the future event will be within the

set Ω , then the set of plausible outcomes will be

$$Y = \{y(u(w), w) : w \in \Omega\}$$

The desirability of a certain outcome may be represented by a set of attributes, and we let $a = \{a_1, \dots, a_n\}$ be the list of attributes that the decision maker is concerned with. We may now imagine a mapping $a(y) = \{a_1(y), \dots, a_n(y)\}$ which represents the desirability of the outcome y . Thus with the set of plausible outcomes Y , we can associate with it a subset $a(Y) = \{a(y) : y \in Y\}$ in the attribute space.

Now we are in a position to discuss the notion of satisfaction. It is difficult to define satisfaction in terms of a measurable quantity, so we will define it in terms of an aspiration level, $a^* = \{a_1^*, \dots, a_n^*\}$, in the attribute space. This is a subjective notion which represents the level that the decision maker is eager to achieve. In many cases, a^* is specified, or implied by the decision maker's superior. In other cases, it is derived from such factors as past achievement records, his competitor's performance records, and other's expectation of him. For the present discussion, we shall not concern ourselves with how the decision maker derives his a^* ; rather, we shall discuss the consequences of having a particular a^* .

Let us concentrate on the attribute space. For illustrative purpose, let us consider the situation where there are two attributes $\{a_1, a_2\}$ and the subset $a(Y)$ is given by A in Figure B1. We assume that an increase in the value of each attribute will increase satisfaction. Referring to Figure B1, if the aspiration level a^* is located at P_1 ,

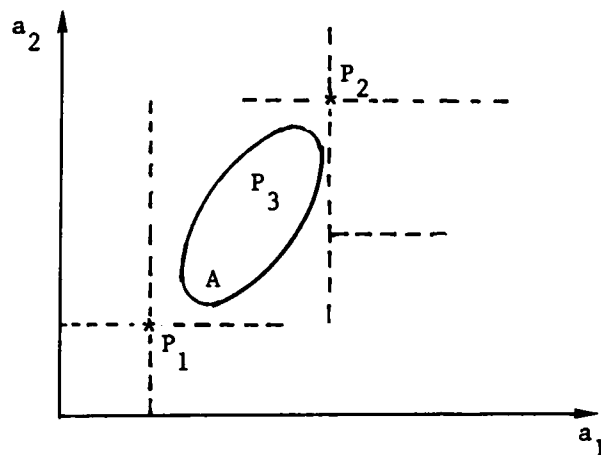


Fig. B1. Attribute space

then we see that for all plausible outcomes Y , the associated attributes exceed the aspiration level, and thus the decision maker would be satisfied with the current operational procedure. If, however, a^* is located at P_2 , then the decision maker would see that under no circumstances will the current operational procedure allow him to achieve his aspiration level. This causes dissatisfaction with the current operational procedure. The ambiguous situation is when a^* is at P_3 . Then, depending upon what plausible outcome is actually realized, the decision maker may or may not be satisfied. Therefore, whether the present operational

procedure is satisfactory, or not, hinges on whether the decision maker can better confine the set of plausible outcomes. That is, reduce Y which in turn shrinks $a(Y)$.

This discussion shows that dissatisfaction is not necessarily a result of ambiguity in plausible outcomes, but rather the possibility that certain plausible outcomes fall short of the aspiration level. Let us define a proxy for dissatisfaction via the weighted expectation gap

$$\bar{\Delta} = \sum_y \sum_{i=1}^n \lambda_i \Delta_i(a_i^* - a(y)) c(y)$$

where

$$\Delta_i(x) = \begin{cases} f_i(x) & \text{if } x > 0 \\ 0 & \text{if } x < 0 \end{cases} ; \quad f_i(x) \text{ is an increasing function}$$

λ_i = relative importance of attribute i (normalized to 1)

$c(y)$ = confidence for outcome y being true (normalized to 1)

The functions $\{f_i(\cdot)\}_{i=1}$, $c(\cdot)$ and weightings $\{\lambda_i\}_{i=1}$ are all subjective and assumed to remain the same for a specific decision maker. Note that in Figure B1 if a^* is at P_2 , $\bar{\Delta} \equiv 0$; whereas $\bar{\Delta} > 0$ if a^* is at P_1 or P_3 . Note, however, that $\bar{\Delta}(a^*=P_3) < \bar{\Delta}(a^*=P_1)$.

Dissatisfaction is a threshold phenomenon and we postulate that the decision maker is unsatisfied if

$$\bar{\Delta} \geq \epsilon > 0$$

where ϵ is a threshold parameter. Thus dissatisfaction is a function of

the aspiration level and the set of plausible outcomes. Next we shall discuss the decision behavior of the decision maker when he is dissatisfied.

Since Y results from both Ω , the set of random future events, and $u(\cdot)$, the operational adjustment rule, then $\bar{\Delta}$ can be expressed as

$$\bar{\Delta}(a^*, u(\cdot), \tilde{c}(\cdot)) = \sum_{w \in \Omega} \sum_{i=1}^n \lambda_i \Delta_i(a_i^* - a(y(u(w), w))) \tilde{c}(w)$$

where $\tilde{c}(w)$ is the confidence in w being true, and $\tilde{c}(w) = c(y(u(w), w))$.

Given a nominal course of action to be taken, we see that the expectation gap is a function of

- the aspiration level,
- the relative confidence on the possibility of different
- future events, and
- the operational adjustment rule.

We postulate that if $\bar{\Delta} > \varepsilon$, then the decision maker will first attempt to reduce $\bar{\Delta}$ by

- improving the operational adjustment rule and/or,
- actively collecting more information in order to reduce the uncertainty about possible future events.

If this still yields a $\bar{\Delta} > \varepsilon$, then the decision maker should realize that there is a problem and begin the options generation process. This is a reasonable model if we assume bounded rationality and that the cost of the options generation process is higher than that of making operational adjustments and collecting information.

From this discussion we see that non-recognition of the problem at the right time might be due to:

- bias on future event assessment,
- incorrect outcome modeling,
- inappropriate aspiration level, and
- bias on relative importance of each attribute.

Each of these factors might be important and in devising an appropriate aid that will facilitate problem recognition we should consider ways for it to:

- help in assessing future events,
- help in determining possible outcomes,
- display the attributes associated with each possible outcome,
- help to improve the operational procedure if needed,
- help facilitate access to information,
- help to set appropriate aspiration levels, and
- prompt the decision maker to enter the options generation phase at the correct time.

The Dynamics of Option Generation

Let us use a simple example to lead into a discussion of a model of the option generation process. Consider a production problem where the goal is to achieve high productivity. For simplicity, let us assume that a production process is represented by

$$y = c(\underline{x}) \quad (1)$$

where y is the output unit, x is the activity vector which contributes to output production. It is also assumed that if a certain activity vector \underline{x} is selected, the total resource required to give such an activity

$$r = f(\underline{x}) \quad (2)$$

Now, the goal of high productivity can have two interpretations. First, for a given resource unit \bar{r} , find an activity vector $\underline{x}^*(\bar{r})$ such that

$$y^*(\bar{r}) \triangleq c(\underline{x}^*(\bar{r})) \geq c(\underline{x}) \quad \forall \quad \underline{x} \text{ s.t. } f(\underline{x}) \leq \bar{r} \quad (3)$$

Second, for a specific output level \bar{y} , find an activity vector $\underline{x}^o(\bar{y})$ such that

$$\underline{r}^o(\bar{y}) \triangleq f(\underline{x}^o(\bar{y})) \leq f(\underline{x}) \quad \forall \quad \underline{x} \text{ s.t. } c(\underline{x}) \leq \bar{y} \quad (4)$$

The first interpretation is to maximize the output subject to resource constraint (the economic view); whereas the second is to minimize the resource required to ensure an output level (the conservation view). Mathematically the two are equivalent if for a given \bar{r} in the first interpretation, $\underline{y} = y^*(\bar{r})$ is used in the second interpretation. However, in general, the two interpretations will yield different answers since neither the desired output nor the resource units are specified.

In fact, the goal does not express any preference on the two attributes: output level, resource requirement. In most cases, the individual tends to interpret the goal statement as one given by (1) or by (2) depending on his subjective view of what seems to be the most important attribute. Thus a certain degree of subjectivity is present in any decision problem. Now, we can define the notion of an option and a good option analytically. An activity \underline{x} is called an option for a given pair (\bar{y}, \bar{r}) if

The set of all options for (\bar{y}, \bar{r}) is denoted by $\Omega(\bar{y}, \bar{r})$. We shall further define partial ordering on the set of activities $\{x\}$ as follows:

$$\underline{x}_1 \gg \underline{x}_2 \quad \text{if} \quad c(x_1) \geq c(x_2) \quad \text{and} \quad f(x_1) \leq f(x_2)$$

That is, \underline{x}_1 "is at least as good as" \underline{x}_2 if \underline{x}_1 uses less (or equal amount of) resource while producing higher (or equal) output. Also, if $\underline{x}_1 \gg \underline{x}_2$ and $\underline{x}_2 \gg \underline{x}_1$, we say they are equivalent, and are denoted by $\underline{x}_1 \approx \underline{x}_2$. An option \underline{x}^* for (\bar{y}, \bar{r}) is said to be a good option for (\bar{y}, \bar{r}) if for all $\underline{x} \in \Omega(\bar{y}, \bar{r})$

$$\underline{x} \gg \underline{x}^* \quad \Rightarrow \quad \underline{x}^* \approx \underline{x}$$

The set of good options for (\bar{y}, \bar{r}) will be denoted $\Omega^*(\bar{y}, \bar{r})$. Given an acceptable performance (\bar{y}, \bar{r}) , the problem of finding all options corresponding to (\bar{y}, \bar{r}) is to determine the set $\Omega(\bar{y}, \bar{r})$; whereas the problem of finding all good options corresponding to (\bar{y}, \bar{r}) is to determine the set $\Omega^*(\bar{y}, \bar{r})$.

Proposition:

Let x^0 be a (good) option for (\bar{y}, \bar{r}) , then it is also a (good) option for (y^0, r^0) if

$$\bar{y}^0 \leq \bar{y} \quad ; \quad \bar{r}^0 \geq \bar{r} \quad (6)$$

Proof:

If x^0 is an option for (\bar{y}, \bar{r}) , then from (5) and (6) we have

$$c(\underline{x}^0) \geq \bar{y} \geq \bar{y}^0 ; f(\underline{x}^0) \leq \bar{r} \leq \bar{r}^0$$

and thus \underline{x}^0 is an option for (\bar{y}^0, \bar{r}^0) . This also implies

$$\Omega(\bar{y}, \bar{r}) \subseteq \Omega(\bar{y}^0, \bar{r}^0)$$

If \underline{x}^0 is a good option for (\bar{y}, \bar{r}) then

$$c(\underline{x}^0) \geq \bar{y} ; f(\underline{x}^0) \leq \bar{r} \quad (7)$$

and for all $\underline{x} \in \Omega(\bar{y}, \bar{r})$

$${}_0\bar{x} \approx \bar{x} \quad \Leftarrow \quad {}_0\bar{x} << \bar{x}$$

Let $\underline{x} \notin \Omega(\bar{y}, \bar{r})$ then either

$$c(\underline{x}) < \bar{y} \quad (8)$$

or

$$f(\underline{x}) > \bar{r} \quad (9)$$

or both. Clearly if either (8) or (9) (or both) is satisfied, then $\underline{x} \not\succ \underline{x}^0$. Therefore, none of the options $\underline{x} \in \Omega(\bar{y}^0, \bar{r}^0)$, $\underline{x} \notin \Omega(\bar{y}, \bar{r})$ will be preferred over \underline{x}^0 . Thus if there exists $\underline{x} \in \Omega(\bar{y}^0, \bar{r}^0)$ such that

$$\underline{x} \gg \underline{x}_0$$

then \underline{x} must be in $\Omega(\bar{y}, \bar{r})$, and thus $\underline{x} \approx \underline{x}_0$. This implies that \underline{x}^0 is a good option for $\Omega(\bar{y}^0, \bar{r}^0)$, and that

$$\Omega^*(\bar{y}, \bar{r}) \subseteq \Omega^*(\bar{y}^0, \bar{r}^0)$$

Thus the (good) option set increases as \bar{y} decreases and \bar{r} increases. Intuitively, this means that if we are demanding less output production while increasing the amount of usable resources, the set of (good) options increases. Conversely, if we are demanding high output production while reducing the amount of usable resources, the set of (good) options decreases. It is conceivable that when the output demand is too high while the usable resource is too low, we have no option.

Let (\bar{y}, \bar{r}) be a specified pair such that $\Omega(\bar{y}, \bar{r}) = 0$, then we shall say that such specification is inconsistent with the productive capability. All the above concepts can be illustrated via Figure B2.

For a given pair (\bar{y}, \bar{r}) , if $\Omega(\bar{y}, \bar{r}) \neq 0$, then it is relatively straightforward to determine $\Omega(\bar{y}, \bar{r})$ and $\Omega^*(\bar{y}, \bar{r})$ if the functions $c(\cdot)$ and $f(\cdot)$ are given analytically. However, the main problem in practice is that neither function is given, and so if x is specified, their evaluation is a time consuming exercise. Under such a situation, a search procedure must be adopted in finding $\Omega(\bar{y}, \bar{r})$ and $\Omega^*(\bar{y}, \bar{r})$.

There are many search algorithms that will allow one to find points in $\Omega(\bar{y}, \bar{r})$ and $\Omega^*(\bar{y}, \bar{r})$, but we will concentrate on those which are closest to human search processes. It is argued that a gradient procedure, which requires that both constraints in (5) are treated equally, is not usually used by a human in his search process because of the

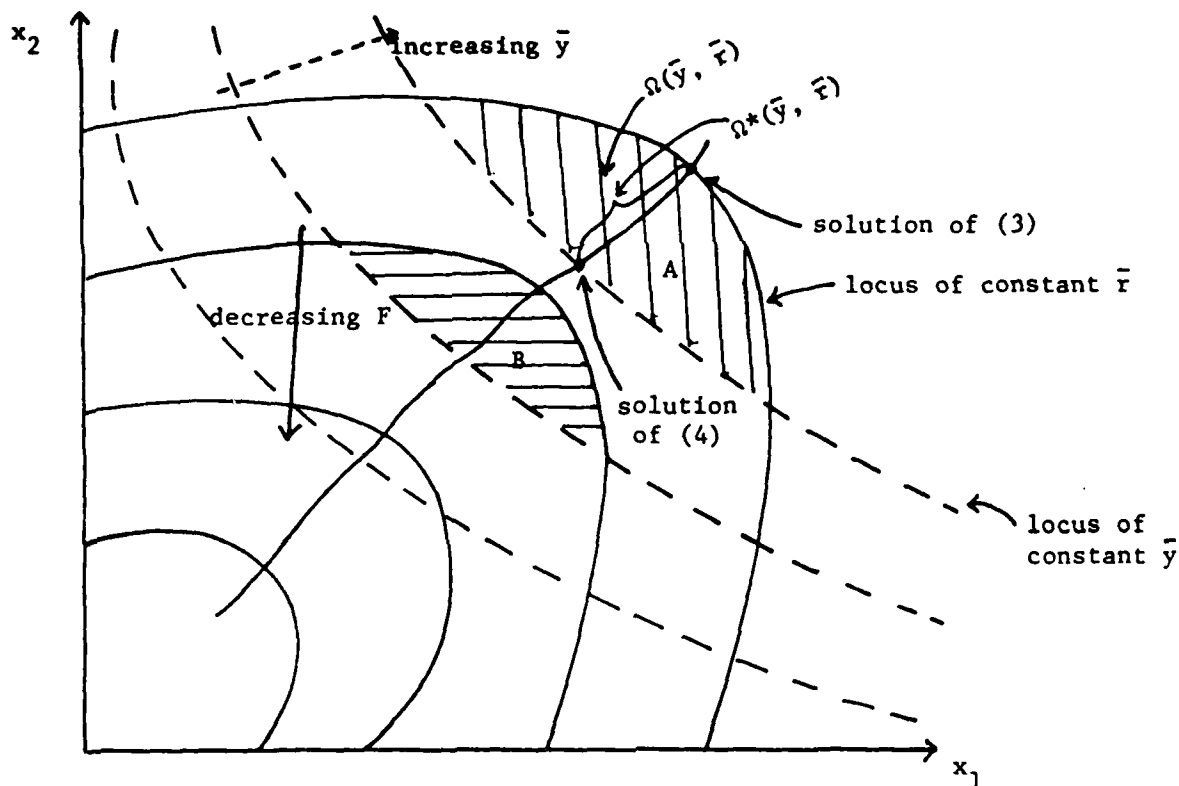


Fig. B2 Illustration for Options and Good Options

limited capability in human evaluation and assessment. Simon refers to this as limited rationality. Below we describe a model for options generation that bears some resemblance to that proposed by Simon.

First, it is assumed that the decision maker will single out one of the constraints as an attribute for attention. He then determines an aspiration level for this attribute. In our example, let us assume that he singles out production as an attribute and sets an aspiration level

$$\text{output} \geq \bar{y}$$

Next, he would list all the activities that influence the level of output, denoting such activities by $\{x_1, \dots, x_n\}$. Then he would determine an appropriate combination of the activities such that

$$c(\underline{x}) \geq \bar{y} \quad (10)$$

If there are no feasible constraints on each activity this is usually possible. Otherwise he may find that no such combination exists, in which case he will reduce the aspiration y . The process iterates until (10) is satisfied.

Next, he would determine the amount of resource units that he would not want to exceed:

$$\text{resource used} \leq \bar{r}$$

If the \underline{x} which is satisfied by the above process is such that

$$f(\underline{x}) \leq \bar{r} \quad (11)$$

then he has found a point in $\Omega(\bar{y}, \bar{r})$. If, however, (11) is violated, then he would focus on the resource requirement and try to generate a new combination \underline{x}' such that

$$f(\underline{x}') \leq \bar{r}$$

and then test to see whether \underline{x}' satisfies the output requirement. The

choice of \bar{x}' is usually obtained by perturbing the components of \bar{x} one at a time. If the functions $c(\cdot)$ and $f(\cdot)$ are reasonably well behaved (convex and concave respectively), then the above iterative process will lead to an option in $\Omega(\bar{y}, \bar{r})$ (region A in Figure B2) if the option set is non-empty. Otherwise, the decision maker has to increase \bar{r} .

The decision maker can, instead of focusing on production, select the resource constraint on the first pass and then iterate as above. This may lead to a different set of options (region B in Figure B2) and good options.

If we believe that the options generation process can be represented by the iterative procedure just described, then we can discuss the issues underlying poor option generation performance.

First, the decision maker may not have a complete list of attributes. This is usually due to the fact that each individual has a subjective view of what the decision problem is and which attributes are important. If the list is incomplete then during the iterative process, all the options generated may fall short in an attribute that is neglected in the whole analysis but which is extremely relevant to the decision problem.

Second, there may be a bias on the initial choice of attribute. The first to be singled out represents the decision maker's subjective view of which attribute is most important for the decision problem. Sometimes emotional and other irrational elements are involved in choosing this attribute, and if the determination of aspiration level for this attribute is too high, then this may result in a few options which completely neglect the other attributes.

Third, there may be incomplete determination of all the activities which will contribute to the particular attribute under consideration. This may be due to lack of knowledge.

Fourth, there may be erroneous determination of the effect of the chosen combination of activities to different attributes. This is due to a wrong model of the real situation. This would typically be the case if the outcome is due to collective actions by different decision makers.

Then finally, the decision maker may have an inefficient search procedure. This is due to the limited capability of an individual to carry out a search by varying several activity components all at once.

APPENDIX C: THE ANALYTIC HIERARCHY PROCESS

The hierarchical value assessment scheme presented here is based on Saaty's approach to hierarchical decision problems[65]. We shall review just the basics of the approach.

In the Analytic Hierarchy Process (AHP) a decision problem is decomposed into levels containing objects with similar attributes. (A level describing objectives and a level describing policies designed to meet these objectives, for example.) The approach is to assign local priorities for each member of a particular level. In particular, one is interested in ways to propagate the local priorities of each level throughout the hierarchy to establish global priorities in a particular level of interest which are a measure of the value of the attribute to the achievement of the overall goal.

Consider, for example, the situation described in Figure C1. The decision maker has to evaluate the relative importance (priorities) of the three policies under consideration; this in turn will help him later in allocating resources to implement these policies. The policies themselves are designed to meet certain objectives (two in this particular case) that contribute to the overall goal the decision maker is trying to attain.

In constructing hierarchical structures other than the one shown in Figure C1, the following guidelines should be remembered:

- (1) The number of levels used in a particular hierarchy is not fixed and should be chosen to reflect the particular problem at hand.

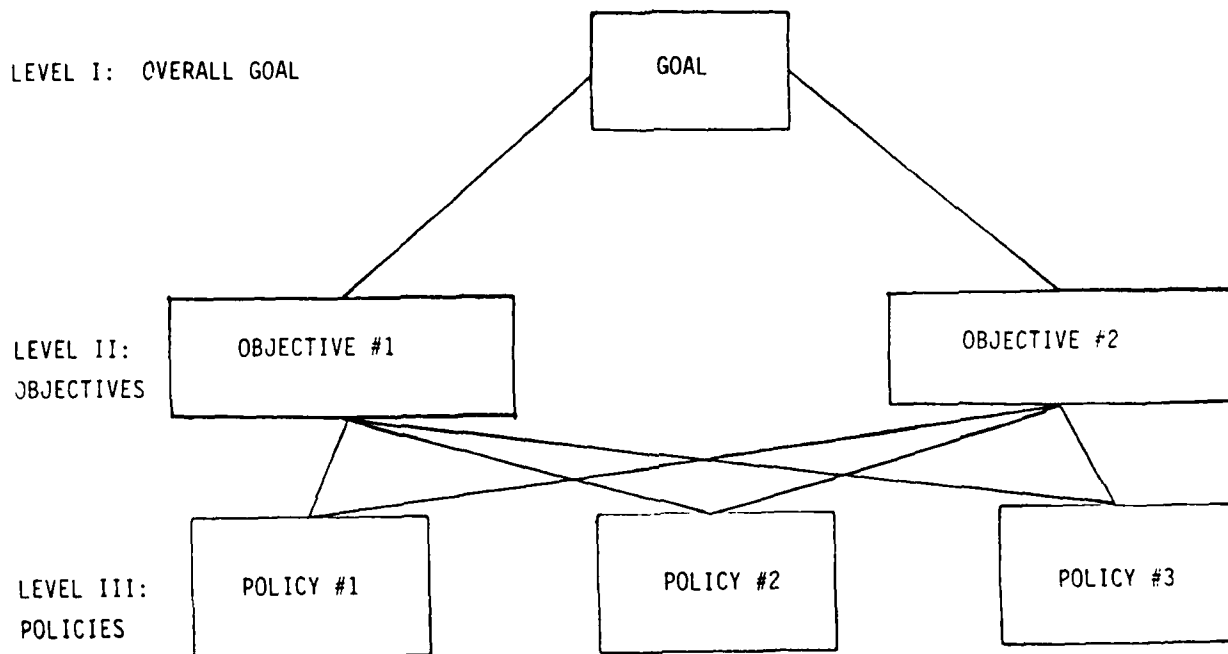


Fig. C1 Hierarchical Policy Evaluation

- (2) The order of the levels should be one that reflects a logical causal relationship between adjacent levels.
- (3) The number of members in a particular level should be chosen to describe the level in adequate detail.

The points mentioned above indicate that the construction of a particular hierarchy is not a process that follows rigid rules, but rather adapts itself to the situation at hand.

Deriving the actual local priorities of members in each level is done through a pairwise between each member of the level relative to a member of the adjacent upper level.

Basic Procedures

Let us start the technical discussion by demonstrating the derivation of the priorities among a set of activities. For illustrative purposes, let us consider three activities denoted by A_i , $i=1,2,3$. We will compare the contribution of these activities to a certain objective. This comparison will be carried out pairwise and the result of the comparison will yield the relative weight, w_i , of the activities under consideration. This pairwise comparison can be summarized in a comparison matrix A given by

$$A = \begin{bmatrix} w_1/w_1 & w_1/w_2 & w_1/w_3 \\ w_2/w_1 & w_2/w_2 & w_2/w_3 \\ w_3/w_1 & w_3/w_2 & w_3/w_3 \end{bmatrix}$$

The information displayed in this matrix is interpreted as follows: every element, a_{ij} , shows the relative contribution to the objective of the i -th activity compared to the j -th activity. That is

$$a_{ij} = \frac{w_i}{w_j} \quad 1 \leq i \leq n, \quad 1 \leq j \leq n,$$

This definition indicates that

$$a_{ij} = \frac{1}{a_{ji}}$$

which results in the matrix A being a reciprocal matrix. Note also that the diagonal elements of matrix A are all 1's.

Returning to the example of Figure C1, we can construct a comparison matrix that shows how each of the three policies contribute to objective #1, say. Every element of this matrix can be obtained using a question of the form

"Consider policy #1 and policy #2, which one contributes more towards objective #1, and what is the strength of this contribution?"

Whenever the ij-th element of the matrix is entered, the ji-th position is automatically entered with the reciprocal value.

To recover the weights, w_i , rather than their ratios we proceed as follows. Note that

$$Aw = nw$$

and since we can write A as the outer product of two vectors

$$A = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \begin{bmatrix} 1/w_1 & 1/w_2 & \dots & 1/w_n \end{bmatrix} \triangleq A_1 A_2$$

then the eigenvalues of are given by

$$\Pi(A) \triangleq |A - \lambda I_n| = |A_1 A_2 - \lambda I_n| = (\lambda^{n-1}) |A_2 A_1 - \lambda| = \lambda^{n-1} (n - \lambda) = 0$$

Hence a comparison matrix has (n-1) of its eigenvalues at the origin and the n-th eigenvalue is equal to the dimension of the matrix.

since $\lambda = n$ is the largest eigenvalue, we conclude that the vector of priorities, w , is simply the largest eigenvector of the matrix A corresponding to the largest eigenvalue. Since we are interested in a relative ordering, this eigenvector is normalized so that its components sum to 1.0.

There are three questions that need to be asked at this point:

- (1) How does the decision maker quantify his judgement of the "strength of contribution" of a certain activity?
- (2) How do we define consistency in this judgement elicitation process?
- (3) How do we proceed with the process across and beyond a given level?

These questions will be discussed briefly in the remainder of this appendix.

The comparison process elicits qualitative judgemental statements that indicate the strength of the decision maker's preference in the particular comparison made. In order to translate these qualitative statements into numbers to be manipulated to establish the required

priorities, a reliable scale has to be established. Much work has been done on the subject of scales in preference statements and we will not repeat the arguments that lead to the employment of a particular scale. Instead we will present a scale that is useful within the AHP paradigm. This is shown in Table C1.

When using this scale, we replace a qualitative comparison statement with the appropriate quantifier. For example, if policy #1 is weakly preferred to policy #2 then $a_{12}=3$ (and by the reciprocity property of A, $a_{21}=1/3$). Performing the complete pairwise comparison for all three policies will result in a 3-by-3 matrix the normalized eigenvector of which yield the importance of the three policies.

In comparing activities, we expect that if activity A_1 is preferred to activity A_2 , and A_2 is preferred to activity A_3 , then activity A_1 should be preferred to activity A_3 . In employing a numerical scale, this transitivity should be maintained throughout the comparison process. Mathematically we define this as

$$a_{ij} = a_{ik} a_{kj} \quad \forall i, j, k \in \{1, 2, \dots, n\}$$

This is simple to understand when we recall that

$$a_{ij} = \frac{w_i}{w_j}$$

So, if we have already established the relative strength of the i -th activity compared to the k -th, and the k -th compared to the j -th, then this should also yield the comparison of the i -th to the j -th. That is

Table C1 Comparison Scale

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgement slightly favor one activity over another
5	Essential or strong importance	Experience and judgement strongly favor one activity over another
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between adjacent scale values	When compromise is needed
Reciprocals of above nonzero	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption

$$a_{ik} a_{kj} \triangleq \frac{w_i}{w_j} \cdot \frac{w_k}{w_j} = \frac{w_i}{w_j} \triangleq a_{ij}$$

When the matrix A is consistent, its largest eigenvalue is equal to its dimension. But when it is not consistent (ie. the consistency condition does not hold for some elements) then the largest eigenvalue of A is always greater than the dimension.

$$\lambda_{\max} > n$$

Then the priority vector is obtained by solving the following eigenvector problem for w

$$Aw = \lambda_{\max} w$$

A consistency index is then

$$C.I. = \frac{\lambda_{\max} - n}{n-1}$$

where in the consistent case CI=0.

Next we consider how to propagate priorities through the hierarchy. Let i (i=0,1,2,...,N) be an index over the levels of the hierarchy. Then i=0 corresponds to the apex of the hierarchy and i=N corresponds to the lowest level. Now let $A_j(i)$ be the j-th activity (or attribute) in the i-th level, $P_j(i)$ be the priority associated with the j-th activity (attribute) in the i-th level with respect to the overall goal (Global

Priority), and $w_{jk}(i)$ be the relative strength of the j -th activity (attribute) in the i -th level when compared with other activities (attributes) in the same level relative to the k -th activity (attribute) in the $(i-1)$ -th level (Local Priority). This is illustrated in

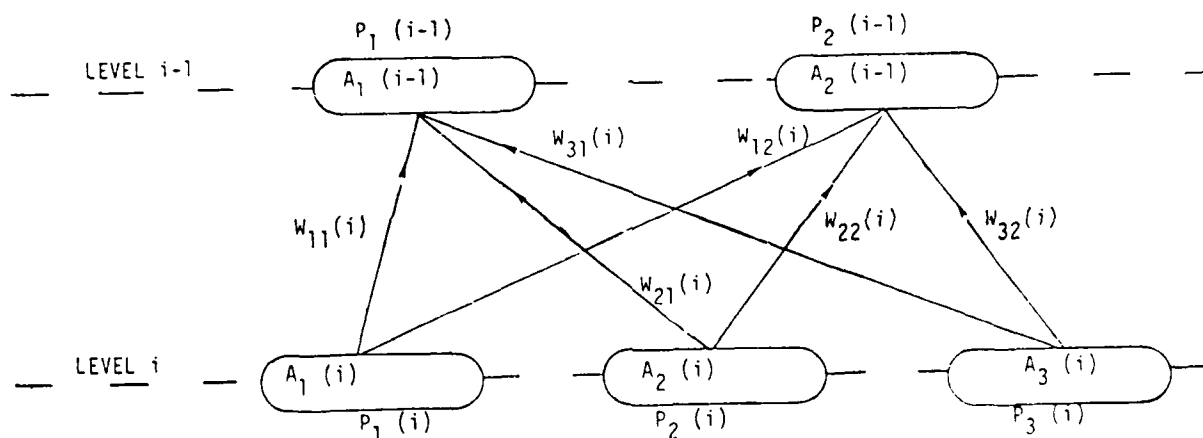


Fig. C2 Adjacent Levels in a Hierarchy

Figure C2 where we depict two adjacent levels of a hierarchy.

In this situation the priorities in the $(i-1)$ -th level have been established, and the next step is to find the priorities associated with the activities of the i -th level. At every level, the priorities are

normalized such that

$$\sum_j p_j(i) = 1$$

The relative strength, w_{ij} , of the activities in the i -th level are found by constructing a comparison matrix of the form

$A_j(i-1)$	$A_1(i) \dots A_k(i)$
$A_1(i)$	A_j
\vdots	
$A_k(i)$	

Thus A_j is constructed after a pairwise comparison of the activities listed with respect to the activity $A_j(i-1)$ which is the j -th activity in the adjacent (upper) level. Once A_j is obtained, we can solve

$$A_j w_j = \lambda_{\max} w_j$$

and the eigenvector w_j is then normalized.

We should remark at this point that:

- (1) The number of A_j matrices to be constructed is equal to the number of activities in the $(i-1)$ -th level, the dimension of these matrices is equal to the number of activities in the i -th level.
- (2) The arrows shown in Figure C2 are drawn to illustrate the direction of the comparison.

Once all A_j matrices are constructed and their normalized eigenvectors are found, the priorities of the i -th level are found from

$$P(i) = [w_1, w_2, \dots, w_k] P(i-1) = W(i) P(i-1), \quad i=1,2,\dots,n$$

where $W(i)$ is the matrix whose columns are the eigenvectors $\{w_j\}$ and the priority of the apex is such that $P(0)=1.0$.

Alternative Method for Computing Priorities

In constructing a pairwise comparison matrix, every element, a_{ij} , is given by

$$a_{ij} = \frac{w_i}{w_j}$$

which is a correct relation if the priorities $\{w_i\}$ were known. When the elements of the matrix are constructed based on judgement, and the use of a ratio scale, one can expect slight deviations. In these cases the elements of the matrix will be given by

$$a_{ij} = \frac{w_i}{w_j} \epsilon_{ij}$$

The values of ϵ_{ij} will be positive and will not deviate much from unity. If we assume that the ϵ_{ij} can be viewed as a random variable, whose natural logarithm is normally distributed around zero, we can derive the priorities as a normalized geometric mean of the rows of the comparison matrix.

Let the comparison matrix A be described by

$$A = \begin{bmatrix} a_1 \\ \vdots \\ a_i \\ \vdots \\ a_n \end{bmatrix} \quad \text{where } a_i \in \mathbb{R}^n \text{ is a row vector}$$

The geometric mean of a row, g_i , is given by

$$g_i = (a_{i1} \cdot a_{i2} \cdots a_{in})^{1/n} = \left(\prod_{j=1}^n a_{ij} \right)^{1/n}$$

Taking natural logarithm on both sides

$$\begin{aligned}\hat{x}_i &\triangleq \ln g_i = \frac{1}{n} [\ln(a_{i1}) + \ln(a_{i2}) + \cdots + \ln(a_{in})] = \\ &= \frac{1}{n} \sum_{j=1}^n \ln(a_{ij})\end{aligned}$$

Since the priority w_i , is defined as the geometric mean, we have

$$\hat{x}_i = \frac{1}{n} \sum_{j=1}^n \ln(a_{ij}) \triangleq \ln(w_i) \quad i=1,2,\dots,n$$

from which we find

$$w_i = e^{\hat{x}_i}$$

To get a normalized vector of priorities we modify the above expression to yield

$$w_i = \frac{e^{\hat{x}_i}}{\sum_{i=1}^n e^{\hat{x}_i}} \quad i=1,2,\dots,n$$

The consistency of the pairwise comparisons can be checked through the multiple correlation coefficient given by

$$R^2 = \frac{n \sum_{i=1}^n \hat{x}_i^2}{\sum_{i < j} (\ln a_{ij})^2}$$

Results are acceptable for values of this coefficient that are greater than 0.9.

The largest eigenvalue of the comparison matrix can be approximated by

$$\hat{\lambda} = n + (n-1) \left[\exp \left(\frac{\sigma^2}{2} \right) - 1 \right]$$

where

$$\sigma^2 = \frac{\sum_{i < j} (\ln a_{ij})^2 - n \sum_{i=1} \hat{x}_i^2}{\frac{n(n-1)}{2}}$$

The advantages of the logarithmic regression approach are in the closed form expressions for computing the priority vector (rather than an iterative process), and in explaining the way this priority vector is derived (a geometric mean of a row vs. an eigenvector corresponding to the largest eigenvalue).

Example: Consider a pairwise comparison matrix given by

$$A = \begin{bmatrix} 1 & 2 & 3 & 2 \\ 1/2 & 1 & 2 & 1 \\ 1/3 & 1/2 & 1 & 1/2 \\ 1/2 & 1 & 2 & 1 \end{bmatrix}$$

$$\hat{x}_1 = \frac{1}{4} [\ln(1) + \ln(2) + \ln(3) + \ln(2)] = 0.6212 \quad ; \quad \hat{w}_1 = e^{\hat{x}_1} = 1.8612$$

$$\hat{x}_2 = \frac{1}{4} [\ln(1/2) + \ln(1) + \ln(2) + \ln(1)] = 0.00 \quad ; \quad \hat{w}_2 = e^{\hat{x}_2} = 1.00$$

$$\hat{x}_3 = \frac{1}{4} [\ln(1/3) + \ln(1/2) + \ln(1) + \ln(1/2)] = -0.6212 \quad ; \quad \hat{w}_3 = e^{\hat{x}_3} = 0.5373$$

$$\hat{x}_4 = \frac{1}{4} [\ln(1/2) + \ln(1) + \ln(1) + \ln(2)] = 0.00 \quad ; \quad \hat{w}_4 = e^{\hat{x}_4} = 1.00$$

The normalized priority vector is given by

$$w^T = [0.4231, 0.2274, 0.1222, 0.2274]$$

Using the eigenvector approach (the HPA program) yields

$$w^T = [0.42, 0.23, 0.12, 0.23]$$

The multiple correlation coefficient is given by

$$R^2 = \frac{n \sum_{i=1}^n (x_i)^2}{\sum_{i < j} (\ln a_{ij})^2} = \frac{4[(0.6212)^2 + (0.00)^2 + (0.6212)^2 + (0.00)^2]}{[\ln(2)]^2 + [\ln(3)]^2 + [\ln(2)]^2 + [\ln(2)]^2 + [\ln(1)]^2 + [\ln(\frac{1}{2})]^2}$$

$$= 0.9867 \quad (\text{acceptable consistency})$$

The estimate for λ is found from

$$\sigma^2 = \frac{\sum_{i < j} (\ln a_{ij})^2 - n \sum_{i=1}^n \hat{x}_i^2}{\frac{n(n-1)}{2}} = 0.0069$$

$$\hat{\lambda} = n + (n-1) [\exp(\frac{\sigma^2}{2}) - 1] = 4.0104$$

CHECK: we should have $AW = \hat{\lambda}w$

$$AW = \begin{bmatrix} 1 & 2 & 3 & 2 \\ 1/2 & 1 & 2 & 1 \\ 1/3 & 1/2 & 1 & 1/2 \\ 1/2 & 1 & 2 & 1 \end{bmatrix} \begin{bmatrix} 0.4231 \\ 0.2274 \\ 0.1222 \\ 0.2274 \end{bmatrix} = \begin{bmatrix} 1.6993 \\ 0.9108 \\ 0.4906 \\ 0.9108 \end{bmatrix}; \quad \hat{\lambda}w = 4.0104w = \begin{bmatrix} 1.6968 \\ 0.9120 \\ 0.4901 \\ 0.9120 \end{bmatrix}$$

The slight inconsistency was introduced through the a_{13} element that should have been equal to 4 instead of 3, using the correct value we find

$$\hat{x}_1 = \frac{1}{4}[\ln(1) + \ln(2) + \ln(4) + \ln(2)] = 0.6931 ; \quad \hat{w}_1 = 2.0000$$

$$\hat{x}_2 = 0.00 \quad (\text{unchanged}) \quad \hat{w}_2 = 0.00$$

$$\hat{x}_3 = \frac{1}{4}[\ln(\frac{1}{4}) + \ln(\frac{1}{2}) + \ln(1) + \ln(\frac{1}{2})] = -0.6931 ; \quad \hat{w}_3 = 0.5000$$

$$\hat{x}_4 = 0.00 \quad (\text{unchanged}) \quad \hat{w}_4 = 1.00$$

and the normalized weight vector is given by

$$w^T = [0.4444, 0.2222, 0.1111, 0.2222]$$

The multiple correlation coefficient for this consistent case is equal to $R^2 = 1$, and the largest eigenvalue is found to be equal to $\hat{\lambda} = 4.00$

Sensitivity of the Priority Vector

A question that keeps coming up quite often is the following: "how large are the perturbations in the eigenvector if the comparison matrix is perturbed by a certain amount?" We can show that if a reciprocal matrix A, is perturbed by a reciprocal matrix P, using elementwise (Hadamard) multiplication (denoted by $A \circ P$), then the new matrix A^* is reciprocal, too. The value of perturbation, Δw , in the original priority vector, w , is found from

$$\Delta w = (\langle y, w \rangle^{-1} - 1) \cdot w$$

where

$\langle y, w \rangle$ is the inner product of y and w .

$\underline{1}$ - is the unity vector

y - is the eigenvector of the perturbation matrix

P - the perturbation matrix is obtained by taking elementwise divisions of elements of the perturbed matrix into those of the original matrix.

An example will demonstrate the use of this formula.

Example: Consider the following comparison matrix

$$A_0 = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 1/2 & 1 & 2 & 2 \\ 1/3 & 1/2 & 1 & 1 \\ 1/4 & 1/2 & 1/2 & 1 \end{bmatrix}$$

The priority (eigenvector) vector of this matrix is given by

$$w_0^T = [0.4747, 0.2551, 0.1630, 0.1072]$$

with consistency ratio equal to CR = 0.017.

One may be interested in finding out what will the changes be in the eigen vector if, instead of A_0 , we consider A_1 given by

$$A_1 = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 1/2 & 1 & 1.5 & 2 \\ 1/3 & 2/3 & 1 & 4/3 \\ 1/4 & 1/2 & 3/4 & 1 \end{bmatrix}$$

The new priority vector is given by

$$w_1^T = [0.4800, 0.2400, 0.1600, 0.1200], \text{ CR} = 0.00$$

Let's use the formula to obtain this new eigenvector. The matrix P is the matrix that when we multiply it elementwise (Hadamard) with the matrix A_0 ,

we obtain the matrix A_1 , i.e.,

$$P = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 0.75 & 1 \\ 1 & 4/3 & 1 & 2/3 \\ 1 & 1 & 3/2 & 1 \end{bmatrix}$$

The eigenvector of this matrix is given by

$$y^T = [0.2495, 0.2335, 0.2422, 0.2761]$$

We want to demonstrate the use of the sensitivity formula, i.e., derive w_1 by using knowledge of w_0 and y . The formula is given by

$$\Delta w = (\langle y, w_0 \rangle^{-1} y - 1) \circ w_0$$

and

$$w_1 = w_0 + \Delta w$$

$$\langle y, w_0 \rangle = 0.2471 \implies \langle y, w_0 \rangle^{-1} y = \begin{bmatrix} 1.0098 \\ 0.9450 \\ 0.9802 \\ 1.1175 \end{bmatrix} \Delta = y_0$$

$$\Delta w = (y_0^{-1}) \circ w_0 = \begin{bmatrix} 0.0098 \\ -0.0550 \\ -0.0198 \\ 0.1175 \end{bmatrix} \circ \begin{bmatrix} 0.4747 \\ 0.2551 \\ 0.1630 \\ 0.1072 \end{bmatrix} = \begin{bmatrix} 0.0047 \\ -0.0140 \\ -0.0032 \\ 0.0126 \end{bmatrix}$$

$$w_0 + \Delta w = \begin{bmatrix} 0.4747 \\ 0.2551 \\ 0.1630 \\ 0.1072 \end{bmatrix} + \begin{bmatrix} 0.0047 \\ -0.0140 \\ -0.0032 \\ 0.0126 \end{bmatrix} = \begin{bmatrix} 0.4794 \\ 0.2411 \\ 0.1598 \\ 0.1198 \end{bmatrix} = w_1$$

The formula demonstrated above relates changes in the comparison matrix to changes in the vector of local priorities; can we relate these changes to the vector of global priorities too?

Let

$p(i)$ = the global priority vector at the i -th level

$p(i-1)$ = the global priority vector at the $(i-1)$ -th level

w_j = the local priority vector relating all elements in the i -th level, to the j -th element in the $(i-1)$ -th level.

Then we have

$$p(i) = [w_1 \ w_2 \ | \ \dots \ | w_i \ | \ \dots \ | w_n] p(i-1) = W_i P(i-1)$$

where W_i is the matrix whose columns are the local priority vectors relating i to level $i-1$.

Change in a comparison matrix results in a change, Δw , in the local priority vector and, therefore, will change also the global priority vector.

Let

\hat{w}_j = new local priority vector resulting from changes in the comparison matrix relating elements in the i -th level to the j -th element in the previous level.

Then

$$\hat{w}_j = w_j + \Delta w_j$$

Now we can define

$$\hat{W} = [\hat{w}_1 \ | \ \hat{w}_2 \ | \ \dots \ | \ \hat{w}_j \ | \ \dots \ | \ \hat{w}_n] = W + \Delta W$$

where

$$\Delta W = [\Delta w_1 \ | \ \Delta w_2 \ | \ \dots \ | \ \Delta w_n]$$

and all the columns of this matrix are obtained from the formula. Then, the new global priority vector, $\hat{p}(i)$, is given by

$$\hat{P}(i) = \hat{W} p(i-1) = (W + \Delta W)p(i-1) = p(i) + \Delta W p(i-1).$$

Concordance Coefficients

The concept of concordance is designed to help determine the overall attractiveness of an alternative course of action. This attractiveness depends not only on the priority assigned to this alternative but also whether it addresses all criteria or just those with the highest priority. The concept of concordance is very useful for the sensitivity analysis associated with the options generation process. This is so because it allows us to identify whether an alternative comes out ahead of the other (on a priority scale) just because it addresses a high priority objective and then, if this objective becomes less important later on (or there was an error in the thinking process that resulted in it having such a high score), it may become of little value because it cannot contribute to the other objectives that may still hold valid.

Global priorities are obtained as a weighted average of local priorities, where the weighting factors are the global priorities of the elements in the previous level. We will define now the global priorities to be a solution of a minimization problem. The global priorities are those that minimize the sum of weighted squared deviations between the local priorities and the global priorities. The weighting factors are the global priorities of the elements in the previous level. That is, the problem is described as follows:

$$\text{Min}_{w_i} \sum_i G_i = \text{Min}_{w_i} \sum_{i,k} P_k (w_{ik} - w_i)^2$$

where

P_k - global priority of k^{th} element in the previous level.

w_i - global priority of i^{th} element in the level under consideration

w_{ik} - local priority of element i with respect to element k in the previous level.

The optimal solution for w_i is obtained from

$$\begin{aligned}\frac{\partial G_i}{\partial w_i} &= 0 = -2 \sum_{k=1}^n P_k (w_{ik} - w_i) = \\ &= -2[(P_1 w_{i1} + P_2 w_{i2} + \dots + P_n w_{in}) - w_i(P_1 + P_2 + \dots + P_n)]\end{aligned}$$

but since, for every level, we have

$$\sum_{k=1}^n P_k = 1$$

we find the optimal global priority to be given by

$$w_i^* = \sum_k P_k w_{ik}$$

which also happens to be the way we computed the global priorities, i.e., the formulation of the optimization problem did not change the way we compute these global priorities. What have we gained?

Before we know the local priorities, w_{ik} , each element in the current level is equally attractive, i.e., its prior global priority is $(1/n)$ and the value of G_i in that case is $G_i^0 = 1/n^2$ (this acts as a null hypothesis). When the local priorities, w_{ik} are known, the global priority, w_i , of the i^{th} element can be computed; this reduces the value of G_i by $(w_i - 1/n)^2$.

A concordance coefficient (analogous to a multiple regression coefficient) can now be defined by

$$C_i = \frac{w_i - 1/n}{\left[\sum_k P_k (w_{ik} - 1/n)^2 \right]^{1/2}}$$

The square of this coefficient provides the relative reduction in G_1 .

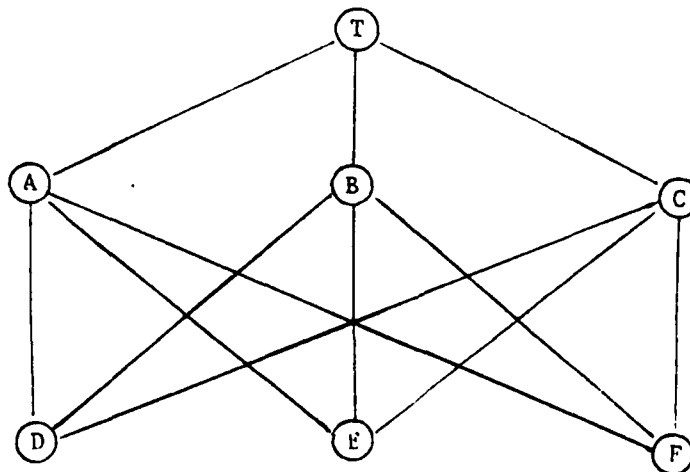
The coefficient of concordance is positive for elements with global priority higher than average, zero for average elements, and negative for below average elements. Elements with great variance in their local priorities will have low concordance coefficients (variances in local priorities affect the denominator in the concordance expression).

Using the global priority and the concordance coefficient for an alternative (or an element in general) one can arrive at several classifications of alternatives. These classifications are not unique but the following guidelines can be used. Priorities which are 20%, or more, higher than the average priority, $1/n$, are considered high. Priorities below 80% of average are considered low. Concordance coefficient greater than 0.50 and less than -0.50 are considered high.

Note that no alternatives will ever be found in the shaded regions, since whenever a global priority drops below average it has a negative concordance coefficient.

Final Remark: The coefficient of concordance serves as a rough indication of the sensitivity of the overall priority with respect to changes in its assessments, or to changes in global priorities of elements in the preceding level.

Example: Consider the following hierarchical decision problem



where the following comparison matrices are given

T	A	B	C
A	1	2	3
B	1/2	1	2
C	1/3	1/2	1

$$\begin{cases} \hat{x}_1 = 0.60 \\ \hat{x}_2 = 0.00 \\ \hat{x}_3 = 0.60 \end{cases} \quad \begin{cases} \hat{w}_1 = 1.82 \\ \hat{w}_2 = 1.00 \\ \hat{w}_3 = 0.55 \end{cases} \quad w_T = \begin{pmatrix} 0.54 \\ 0.30 \\ 0.16 \end{pmatrix}$$

A	D	E	F
D	1	7	6
E	1/7	1	2/3
F	1/6	1.5	1

$$\begin{cases} \hat{x}_1 = 1.25 \\ \hat{x}_2 = -0.78 \\ \hat{x}_3 = -0.46 \end{cases} \quad \begin{cases} \hat{w}_1 = 3.43 \\ \hat{w}_2 = 0.46 \\ \hat{w}_3 = 0.63 \end{cases} \quad \hat{w}_A = \begin{pmatrix} 0.76 \\ 0.10 \\ 0.14 \end{pmatrix}$$

In a similar way we get

B	D	E	F
D	1	1/6	1/5
E	6	1	2
F	5	1/2	1

$$w_B = \begin{pmatrix} 0.08 \\ 0.58 \\ 0.34 \end{pmatrix}$$

C	D	E	F
D	1	1/8	1/6
E	8	1	2
F	6	1/2	1

$$w_C = \begin{pmatrix} 0.06 \\ 0.59 \\ 0.34 \end{pmatrix}$$

and global priorities are given by

$$\begin{pmatrix} w_D \\ w_E \\ w_F \end{pmatrix} = \begin{pmatrix} 0.76 & 0.08 & 0.07 \\ 0.10 & 0.58 & 0.59 \\ 0.14 & 0.34 & 0.34 \end{pmatrix} \begin{pmatrix} 0.54 \\ 0.30 \\ 0.16 \end{pmatrix} = \begin{pmatrix} 0.45 \\ 0.32 \\ 0.23 \end{pmatrix}$$

The concordance coefficients are found from

$$C_i = \frac{w_i - 1/n}{\left[\sum_{k=1}^3 P_k (w_{ik} - 1/n)^2 \right]^{1/2}}$$

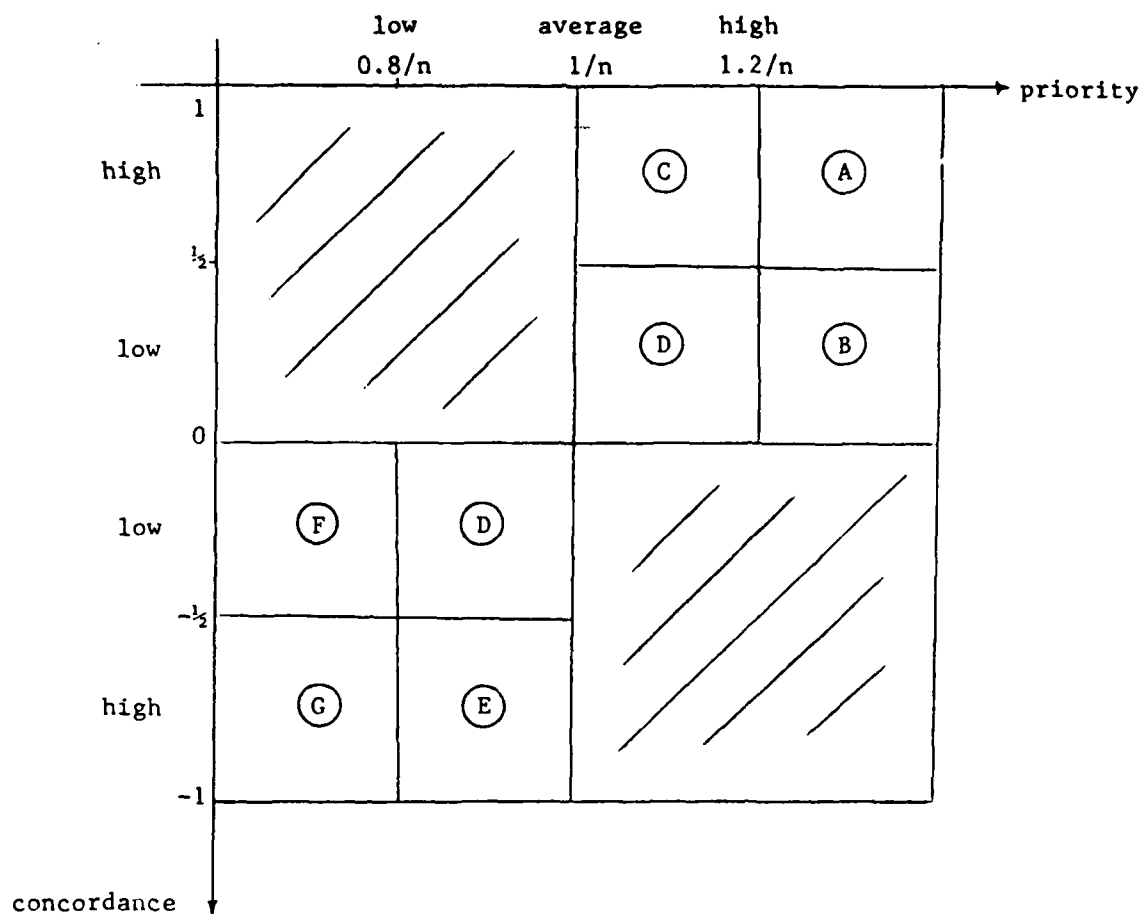
therefore, we find

$$C_D = \frac{0.45 - 0.33}{\sqrt{0.54(0.76 - 0.33)^2 + 0.30(0.08 - 0.33)^2 + 0.16(0.06 - 0.33)^2}} = 0.32$$

$$C_E = \frac{0.32 - 0.33}{\sqrt{0.54(0.10 - 0.33)^2 + 0.30(0.58 - 0.33)^2 + 0.16(0.59 + 0.33)^2}} = -0.05$$

$$C_F = \frac{0.23 - 0.33}{\sqrt{0.54(0.14 - 0.33)^2 + 0.30(0.34 - 0.33)^2 + 0.16(0.34 - 0.33)^2}} = -0.70$$

Plotting the priorities and concordance coefficients we get the following description:



Legend:

- (A) a very good choice
- (B) a good choice with some weak points
- (C) a good compromise
- (D) an average choice
- (E) a mediocre compromise
- (F) in general a bad choice with some good points
- (E) an inferior element

From this we see that only alternative D falls in an acceptable region while both E and F are unacceptable (E is better than F, though).

APPENDIX D: STIMULUS MATERIAL FOR THE STANFORD EXPERIMENT

This appendix contains copies of a selection of the stimulus material used by the subjects in the Stanford Experiment. It is self explanatory and includes the basic introductory material received by all subjects, the Simple Environment and the Post-Test Questionnaire.

EXPERIMENTAL DESCRIPTION PROTOCOL

Good [morning
afternoon], thank you for agreeing to participate in this experiment. We are trying to devise ways of helping decision makers in the generation of creative solutions to complex decision problems, and the purpose of the experiment today is to test the effectiveness of one of the aids that will be provided.

Both before you begin, and when you finish, we will ask you to fill out a simple questionnaire, that is designed to provide us with some attitudinal information.

The experimental session proper will start when you are given a description of the problem and an introduction to the aids. The session can last up to two hours, but you may stop whenever you feel you have completed the task. One of us will be present at all times and will answer any questions concerning the experimental procedures.

Remember that this is not a test of your ability but is simply a way of helping us define some useful decision aids.

Pre-Test Questionnaire

The prupose of this questionnaire is to establish some basic biographical data, and to determine your prior knowledge about the problem you will be asked to work on. We hope to be able to correlate this information with the results we obtain from our experiments.

Please answer all the questions. When you have finished, return the questionnaire to the experimenter. Thank you.

Name: _____

Age: _____

Sex: Male _____ Female _____

Status at Stanford: (circle) 1st year 2 3 4 graduate

Major area of study: _____

Your home town/state: _____

Do you know of the Med-Fly infestation in the Bay Area? Yes _____ No _____

If yes, then how would you describe your knowledge of the problem and attempts to solve it?

Marginal

Very Detailed

Have you heard that there have been attacks on women on the Stanford Campus over the last six months? Yes _____ No _____

If yes, then how would you describe your knowledge of the problem and attempts to solve it?

Marginal

Very Detailed

THANK YOU for agreeing to participate in this experiment. Should you have any questions, a member of our team will be present in the room at all times. Take as much time as you need to complete the experiment. Note that this is not a test of your personal ability.

Please begin by reading the OVERVIEW on the following page.

OVERVIEW

We are interested in aiding individuals in generating alternatives (options) to solve a problem (achieve a goal). This is especially important in stressful situations, where people typically generate a very limited number of solutions.

Our proposed "aid" is a package of tools including:

INFORMATION - A selection of information that may be relevant to the problem.

STRUCTURING AIDS - Tools to help organize the basic elements of the problem.

CREATIVITY AIDS - Tools designed to stimulate creative thinking.

After completing a few preliminary tasks, you will be presented with three envelopes, each containing one of the above set of tools. You may use all, some or none of the aids, and in any order. You may regard the use of the aids much like you would approach a buffet: there are appetizers, entrees and desserts to select from. You may eat anything you wish, in any amount and in any order.

The goal of this experiment is to generate options for the problem posed on the following page. Remember that there are no right or wrong answers.

Now please read the problem.

CAMPUS SECURITY SCENARIO

Since October, 1981, there have been a number of assaults and rapes on the Stanford campus. The first attack occurred in early October, at 8:30 p.m. near Tresidder Memorial Union. On November 5, at 10:30 a.m., a woman was attacked while jogging near the stadium. Several days later, a third woman was attacked at 5:45 p.m., as she walked between Memorial Church and building 50. Two men were believed to have been involved in the latter case, but the victim's eyes were covered, and no description was possible. In mid-December, at about 6 p.m., a woman was accosted in the parking lot near the Physics Tank, and threatened with kidnap. The latest incident took place on January 5, when a woman was assaulted shortly after 1:00 p.m. in the Arobretum near the Stanford Mausoleum.

The Stanford Police Department increased both uniformed and plain-clothes patrols. The Santa Clara County Sheriff's Department increased coverage of the campus by patrol units. The A.S.S.U. bought and gave out several thousand whistles, with the instructions to blow them if you are attacked or hear someone in trouble, and to move toward the whistle if you hear it. The University now allows parking in A lots after 3:00 p.m., so that women may move their cars closer to the buildings before evening.

Consider yourself a member of a special advisory panel set up by the President's office. Your task is to generate as many solution or partial remedies to the campus security problem. The solutions may apply at any level--actions individuals may take, or the University, the Stanford Police Department, or any level at which you can generate an option. Aim for as many ideas as you can, even if they don't initially appear feasible. Other members of the advisory panel may be able to use your idea as a jumping off point. Just try to come up with as many possible approaches to the problem as you can.

Now that you have read the scenario, please describe the problem in your own words on the sheet labeled PROBLEM DESCRIPTION.

- turn to next page -

At this time, please record any initial solutions (options) you may have on the sheet labeled INITIAL OPTIONS.

- turn to next page -

Inform the member of our team present that you are now ready to utilize the aids to try to generate more options for the problem you read earlier. You will find more detailed information about each set of tools on the face of the envelopes.

Please record any new options on the sheet labeled NEW OPTIONS. When you feel that you have completed the experiment, please notify the member of our team present.

Thanks again!

STRUCTURING AIDS

In this package you will find two tools designed to help you think about the structure of the problem.

1. A simple checklist
2. A structure template

The first of these is very straightforward and is really just a way of reminding you of various aspects of the problem. The second is more elaborate and requires you to make a conscious explicit effort to record the main elements of the problem.

Use these aids only if you need to. View them as tools for problem solving, and not as tasks that must be completed.

CHECKLIST STRUCTURING AID

In thinking through the campus security problem, you may want to consider the following aspects:

ECONOMIC

ENVIRONMENTAL

POLITICAL

SOCIAL

Structuring Template

The purpose of the aid is to help you organize the important elements of the problem. Going through this exercise should improve your understanding, and help you generate more options.

On the attached sheet you will find a series of empty boxes with labels at the left hand edge. The idea is to enter a brief description of the labeled aspect of the problem. So, in one box at the Actors level you could write "students" Use as many boxes as you need at each level, and add more boxes if necessary. By writing down as many actors---people, groups, or even nonhumans---you may be able to consider the problem from their perspective, and so generate more options than if you just consider the problem from one perspective. Also, you may stumble onto the resources of a group which you totally forgot to consider. You may see how to satisfy the goals of one subset of the actors, and solving a subproblem is a step to solving the whole problem. In short, the structuring template is meant to stretch your conception of the problem, broaden it as much as you can, and give you ideas about attacking the problem in different areas.

The structuring template is not to be considered a whole extra problem. Use it as much or as little as you wish. As you fill it out, write down any options that occur to you on the sheets labeled "new options".

An example of a template filled out by someone working on the problem of medflies in the Bay area is provided as a guide.

Structuring Template

Overall Goal					
Actors					
Actors Goal					
Resources					
Constraints					
Environmental Factors					

Structuring Template

Overall Goal	Solve Medfly problem					
Actors	Scientists	Politicians	Residents	Farmers	Fruit buyers	Eradication project workers
Actors Goal	Develop strategies to eradicate or contain medflies	Solve problem without upsetting voters	protect health and safety	protect crops avoid losses	ensure the quality of fruit bought to make money	carry out eradication program properly
Resources	technology, money workers	Money, talk, political authority	public opinion	economic contributions to state, fruit	threat of embargo	trucks, helicopters manpower, sprays protective gear
Constraints	avoid environmental damage, stay within budget, restricted to present technology	don't overstep party doctrine constituent opinions	lack of authority	limited individual resources, difficult to change profession	satisfy demand for fruit	avoid personal harm
Environmental factors	try not to harm anything but medflies		preserve our fruit, health of family and pets enjoy outdoors	protect farms and health, growing season		hilly terrain, angry residents, rain.
						can't live in really cold weather, or spread far without people
						fly up to 2 miles eat numerous kinds of fruit, reproduce quickly
						eat, reproduce
						Medfly

CREATIVITY AIDS

In this package you will find three tools designed to stimulate your creativity

1. Challenge Assumption Protocol
2. Free Associations
3. Brainstorm Questions.

All are straightforward and selfexplanatory, although #1 will probably require most effort to use.

Do not feel obliged to use these tools. Work with them only when and if you want to. Remember that they are aids for problem solving, not problems themselves.

FREE ASSOCIATIONS

Sometimes it's useful to take a break from a problem and think in one entirely different area. To help you do so, we will give you a series of cue words. Read one cue word, and to respond with the first word which comes into your mind. Write it in the blank next to the cue word. Then go on to the next cue word. Continue for all of the cue words.

<u>CUE WORDS</u>	<u>RESPONSE</u>
1. rabbit	_____
2. conceal	_____
3. orbit	_____
4. kitchen	_____
5. fragment	_____
6. hinge	_____
7. kiwi	_____
8. petals	_____
9. electric	_____
10. random	_____
11. ski	_____
12. horoscope	_____
13. dancing	_____
14. antibody	_____
15. proud	_____

BRAINSTORM QUESTIONS

One way of creating a new view of the problem is to ask yourself thought-provoking questions such as those that appear on the following page.

If, in thinking through these questions, new options, or modifications to existing ones, occur to you then please enter them on the worksheet labelled "New Options". Feel free to spend as much time as you need on this process.

- Have I Thought-up all the phases of the problem?
- Which sub-problems seem most important?
- Is there data that might help?
- Where might this data be found?
- What ideas do I have so far?
- How would I begin to test the validity of the options I've generated so far?
- Have I imagined all possible contingencies?

CHALLENGE ASSUMPTIONS PROTOCOL

A good way of generating insights into a problem is to make a list of your assumptions, and then challenge it.

Start by briefly stating your assumptions on the sheet labeled ASSUMPTIONS. Please give this task careful thought, as many times we are not consciously aware that we have made assumptions. For example, if you heard the word "newlyweds", you are likely to be inclined to envision a young man and woman when in fact, the newlyweds could be senior citizens.

After recording your assumptions on the left side of the sheet, choose the most restrictive one in your estimation, and examine the consequences of assuming it is not true. To help you do that, try to write down its negation on the right side of the paper, and do so in a positive way. For example, instead of writing:

ASSUMPTION

gravity

NEGATED ASSUMPTION

no gravity

write:

ASSUMPTION

gravity

NEGATED ASSUMPTION

people float

Try to use the negated assumption, however implausible it may seem.

Continue to do this for all assumptions.

If at any time you find that new options, or modifications to existing ones, occur to you, please remember to include them on the sheet labeled NEW OPTIONS. Feel free to spend as much time as you need on this process.

ASSUMPTIONS

ASSUMPTION

NEGATED ASSUMPTION

1.

1.

2.

2.

3.

3.

.

.

.

.

.

.

Post-Test Questionnaire

The purpose of this questionnaire is to get your opinion about the experimental procedures you have just experienced. Please be as frank and honest as possible in responding to these questions. Your answers will be entirely confidential and will be used only as supporting anecdotal evidence in any conclusions we reach as a result of this experiment.

Q1. Do you think that the overall procedure helped you generate more solutions than you might have if left on your own? Please explain.

Q2. What were your general impressions of the experimental procedure?

Q3. Were any of the tools especially useful to you? Please explain.

Q4. Did any of the tools seem inappropriate? Please explain.

Q5. Can you think of any tools or aids you would have found useful, but which were not provided? If so, please explain.

Q6. Are there any other remarks you would like to address to us?

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END